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THE AGRICULTURAL ECONOMICS OF FREMONT IRRIGATION: A CASE  
STUDY FROM SOUTH-CENTRAL UTAH

by

Chimalis R. Kuehn

A thesis submitted in partial fulfillment  
of the requirements for the degree

of

MASTER of SCIENCE

in

Anthropology

Approved:

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UTAH STATE UNIVERSITY  
Logan, Utah

2014

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## ABSTRACT

The Agricultural Economics of Fremont Irrigation:  
A Case Study from South-Central Utah

by

Chimalis R. Kuehn, Master of Science

Utah State University, 2014

Major Professor: Dr. Steven R. Simms  
Department: Sociology, Social Work, and Anthropology

This thesis compares hypotheses about Fremont agricultural investment to evaluate the relationship between dry or rainfall farming and irrigation farming. Recent identification of a Fremont irrigation feature at Pleasant Creek provides an opportunity to study farming commitment through labor investment. A comparison of relative efficiencies of irrigated and dry-farmed maize using experimental digging exercises and cross-cultural comparisons generate data about the range of investment, carrying capacity, and the contexts of selection operating under circumstances like those at Pleasant Creek.

The analysis shows that irrigated maize efficiency remains equivalent to or lower than dry-farmed maize. Irrigation labor costs influence maize return rates more with fewer years of canal operation and suggest that technological investment in irrigation at the project site would be “worth it” only with anticipated long-term commitment. For instance, labor costs of irrigation amortized over time show that initial construction costs

no longer affect energetic return rates of maize after four to six years of canal use.

Beyond this span of time, field labor and processing time condition overall return rates more than distinctive labor costs of irrigation.

The application of carrying capacity scenarios indicates the canal likely supported between 30 and 100 individuals. Analysis of infrastructural complexity and labor group size suggests that Pleasant Creek was home to a group operating within complexity beyond egalitarian forager organization. The level of investment and productivity suggests a community, likely bound by kinship ties with a corporate management style, engaged in subsistence-level agriculture that served to expand the farmable area and reduce the risk of food shortage in an agriculturally marginal area.

(135 pages)

## PUBLIC ABSTRACT

The Agricultural Economics of Fremont Irrigation:  
A Case Study from South-Central Utah

Chimalis R. Kuehn

Recent identification of a Fremont irrigation feature in southern Utah provides an example from which to study costs and benefits of intensive agricultural investment by the Fremont. Studying irrigation investment informs our understanding of cultural process behind subsistence decisions, as well as of cultural complexity among the temporally and geographically diverse Fremont farmers.

Fieldwork, funded in part by Undergraduate Research and Creative Opportunities (URCO) Grants, included experimental canal digging with wooden stick tools and excavation of a subsurface canal feature. This study uses prehistoric canal dimensions and labor rate data to compare relative efficiencies of irrigated and dry-farmed maize. Analysis shows that irrigated maize efficiency remains equivalent to or lower than dry-farmed maize with a 20 to 50 percent increase in labor investment. An irrigation strategy at the project area likely represented a marginally more costly endeavor resulting in greater productivity that reduced the risk of crop failure in an arid region. Carrying capacity estimates for this system indicate irrigation could have supported a community interacting on a level of social complexity beyond that of egalitarian forager-farmers. Overall, this research contributes to growing literature on Fremont cultural complexity and how the dynamic Fremont fit in with neighboring farmers and foragers.

## ACKNOWLEDGMENTS

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Chimalis R. Kuehn

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## INTRODUCTION

Recent investigations of a possible Fremont farming site at Pleasant Creek support the use of irrigation by prehistoric farmers in southern Utah (Simms and Kuehn 2012). Irrigation represents a form of intensive agriculture and, like the initial transition to agriculture itself, has been associated with dependence on food production, population growth, sedentism, and growing social complexity (Adler et al. 1996; Boserup 1965; Wittfogel 1957). However, large- and small-scale societies across the world employ irrigation technology at varying scales of investment that carry different implications for the importance of food production in given communities or time periods (Diehl 2011; Doolittle 1990; Lees 1994; Scarborough 1991). The role irrigation might have played in intensification and social change within the temporally and geographically variable subsistence of Fremont farmers in Utah remains unclear.

The Fremont of the Great Basin and Colorado Plateau represent a diverse group of foragers and farmers distinguished by common material remains. The degree of investment in domesticated crops and farming technology varied with fluctuations in mobility and settlement (Madsen and Simms 1998; Simms 1990). By comparing the economic benefit of maize farming against wild plant foods, Barlow (1997) concluded that variation in Fremont agricultural commitment likely resulted from differential availability of wild resources. Additionally, farming investment among the Fremont should intensify with diminishing opportunities for high-ranked resources, as well as when energetic return rates remain low for both farming and foraging during a growing season (Barlow 2006). Building from Barlow's (1997, 2006) analysis, I use the Pleasant

Creek irrigation site as an example to investigate the relative efficiency of irrigated maize compared to dry-farmed maize, as well as to evaluate the level of investment in farming here that may be indicative of a more widespread regional pattern.

Level of investment also provides insight into mechanisms of power and cultural complexity. Anthropologists and historians associate irrigation with growing cultural complexity for several reasons. The administration of irrigation facilities may contribute to cultural complexity in some circumstances of scale or distribution if population density, centralized and hierarchical settlement, and centralized authority reflect complexity (Billman 2002; Steward 1955; Wittfogel 1957). However, in many cases, there exists no causal relationship as irrigation, social complexity, and centralized authorities can evolve together but independently (Adams 1971; Davies 2009; Lees 1994). Nevertheless, aspects of power and social organization remain tied to irrigation activities. A need for cooperative labor management, as well as water and harvest distribution often accompanies an irrigation project. Levels of complexity in management tasks may reflect or encourage hierarchical power distribution and social order (Davies 2009; Wittfogel 1957). Meanwhile, irrigated crops create limited patches of reliable, productive resources and differential access to these resources contributes to differences in social standing, creating a dynamic between “haves” and “have nots,” and allowing the rise of those that control access to water and resources (Adams 1971:602; Billman 2002:374; Davies 2009).

The organization of people around irrigation investments also has implications for complexity. Reduced mobility and the establishment of permanent or semi-permanent settlements frequently co-occurs with the adoption of agriculture in order to reduce

transport costs of resources and labor in agriculturally marginal areas while also protecting intensive investments at these locations (Adler et al. 1996; Leonard and Reed 1993; Upham 1994). Population aggregation carries with it parallel needs for social organization and management to appropriately deal with shared spaces and resources (Flannery 1969). Aggregation may result from the labor needs of irrigation, as well as the gathering of people around an engineered oasis. Settlement size and population distribution of irrigation communities can reflect degrees of complexity and centralized organization (Billman 2002). Additional factors influencing aggregation and sedentism often include warfare and defense, trade, or religious integration (Adler et al. 1996).

A discussion of agricultural investment and social complexity associated with irrigation applies to the Fremont case because we do not know what kind of social and economic environment existed for the farmers at Pleasant Creek or how variable social form may have been across the Fremont region. In order to escape normative classifications and limiting explanations, researchers have interpreted the Fremont archaeological record as the result of evolutionary processes operating within changing contexts of selection (Madsen and Simms 1998:280). The initial adoption of farming, for instance, brought changes to context by introducing new behavioral options while also affecting changes to population size and distribution that would modify a regional environment of forager and farmer interaction (Madsen and Simms 1998). Within this framework, agricultural intensification among the Fremont is an alternative adaptation in the behavioral mix that represents both a response to and modifier of selection contexts. Analysis of the economic and environmental circumstances of investment can help to model the range of intensification, the relative economic stability, and the social

environment associated with the level of intensification to understand contexts of selection operating within circumstances like those at Pleasant Creek.

## RESEARCH OBJECTIVES AND HYPOTHESES

The Pleasant Creek irrigation site offers a unique opportunity to learn about Fremont agricultural intensification through modeling the agricultural economics of irrigation investment. My objective here is to compare the energetic return rates of irrigation and rainfall farming in order to understand the conditions under which the Fremont would irrigate. This analysis involves comparing high- and low-cost irrigation scenarios with the reported range of dry farming investment (Barlow 1997, 2002). The scale of investment in irrigation made evident from this analysis will help to develop inferences about the socio-political implications of Fremont irrigation at the project site. The primary research question explores relative efficiency of farmed maize while the second targets social complexity (Table 1). Does irrigation at the project site reflect a hierarchical, socially complex society or a less-complex arrangement? Two hypotheses informed by cross-cultural analogy will be tested: (1) Fremont irrigation at Pleasant Creek reflects a small-scale investment accomplished by a small, relatively mobile community within a mixed forager-farmer economy employing an egalitarian, corporate means of authority; or (2) Fremont irrigation at Pleasant Creek reflects a large-scale investment involving multiple administrative levels of society and increased cultural complexity resulting from population growth and a shift toward hierarchical organization. Cross-cultural data contributes to the development of expectations shown in Table 1. For example, research on the development of social complexity informs the comparative expectation of 100 to 250 people. Billman (2002) supposes that political authority rose above that of an informal, ephemeral leadership system with the establishment of formal



Table 1. Objectives and Expectations

Research Question	Hypothesis	Expectations
What is the relative efficiency of irrigated vs. dry/rainfall farming at the Pleasant Creek site?	(1) Irrigation represents an energy efficient investment.	<ul style="list-style-type: none"> <li>• Under most conditions, irrigated maize produces a higher energetic return.</li> </ul>
	(2) Irrigation represents a less efficient investment.	<ul style="list-style-type: none"> <li>• Irrigated maize produces a lower energetic return under most or some conditions.</li> </ul>
What are the socio-political implications of Fremont irrigation?	(1) The system is a small-scale investment requiring local labor organization that could be managed by a corporate kin group.	<ul style="list-style-type: none"> <li>• Limited agricultural infrastructure (i.e. number of canals, field features, etc.)</li> <li>• Work force and supportable population of need of less than 100 to 250 people</li> <li>• Low population/site density</li> </ul>
	(2) The system is a large-scale investment engineered with hierarchical authority in a society with increasing levels of complexity. Could resemble a heterarchy or sequential hierarchy.	<ul style="list-style-type: none"> <li>• Complex agricultural infrastructure</li> <li>• Work force and supportable population of more than 100 to 250 people (several hundred to thousands)</li> <li>• Settlement hierarchy and high population density</li> </ul>

administrative levels. He suggests that the lowest administrative levels manifest as corporate leadership or designated authority figures with populations of 100 to 250 people. The data presented here focuses on the potential demographics associated with irrigation investment and briefly touches on issues of settlement. Future research involving regional patterns can best address the broader implications of social change associated with agricultural intensification among the Fremont.

The Pleasant Creek project location includes remnants of a nearly complete irrigation system identified from likely stream diversion to debouchment (Figure 1). The suspected intake begins near the head of Pleasant Creek in a subalpine meadow, and the canal empties onto a sandy, alluvial plain known as Jorgenson Flat about 7 km to the northeast. The overall dataset consulted to address the objectives (Table 1) includes canal capacity, irrigable area, productivity, work force needs, and sustainable population size. Estimates for canal hydraulics and irrigable area derive from the morphology of subsurface channel features discovered in test trenches while estimates of sustainable population size result from reports of daily or annual caloric requirements. Data on local environmental conditions help to model productivity for Jorgenson Flat, and a review of literature reporting costs and benefits of dry and irrigated maize agriculture supports the comparison of energetic return rates for Fremont farming strategies (Arbolino 2001; Barlow 1997; Herhahn and Hill 1998; Logan and Sanders 1976; Mabry 2002, 2005). As all costs and benefits reflect a range of conditions, I analyze the energetic statistics of irrigation according to the least and most costly scenarios.

Analyzing a range of costs and benefits derived from partially reconstructing the

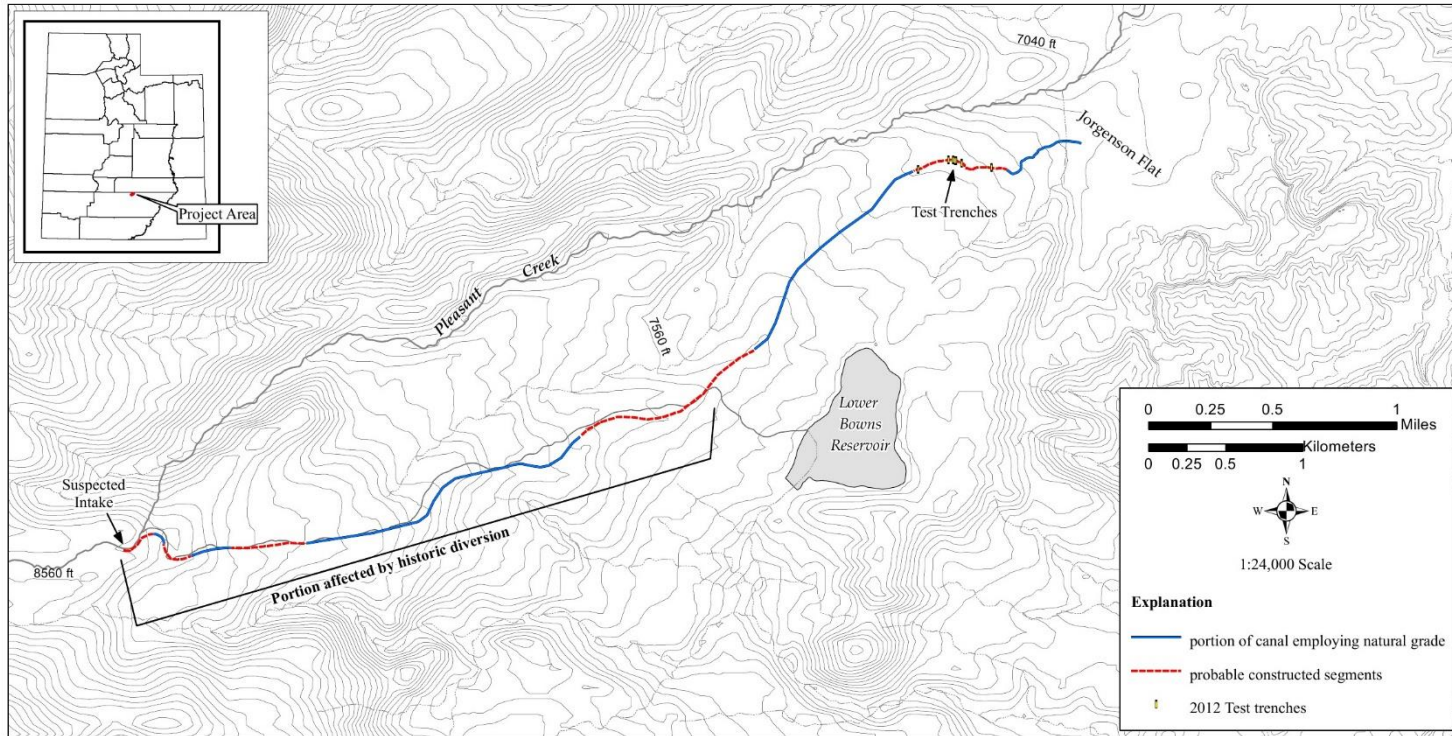


Figure 1. Project Location Map

particular Pleasant Creek scenario allows the project site to serve as an example from which to investigate other cases of Fremont irrigation. Although this represents the first example of a complete Fremont irrigation system investigated by archaeologists, the practice of irrigation was likely more common than current documentation of Fremont irrigation suggests. This economic analysis draws on hypothetical scenarios of assumed prehistoric intent and environmental conditions that ultimately reflect behavioral variability; however, the comparison of costs and benefits here should reveal a robust relationship associated with cultural processes behind subsistence decisions. Future research involving the local paleoecology, the geomorphology and use-life of the irrigation feature, and surrounding settlement locations will provide further insight into the context of irrigation at the project site.

## RESEARCH BACKGROUND

### *The Fremont Culture*

The study area falls along the Pleasant Creek drainage, a perennial stream originating on Boulder Mountain just east of the Aquarius Plateau in south-central Utah (Figure 1). Pleasant Creek flows nearly 30 km until it terminates in the Fremont River. During his early twentieth century fieldwork for the Harvard Peabody Museum, Noel Morss (2009) investigated sites along the Fremont River drainage, eventually naming the distinctive cultural remains he found there “Fremont.” The Pleasant Creek area falls on the northern Colorado Plateau, along the northern periphery of the Ancestral Puebloan culture.

The archaeology of the immediate area around Pleasant Creek still reflects Morss’s initial description, consisting of “dwelling caves, storage places, and rock-circle sites” that sometimes show a connection to Puebloan culture but are predominantly a Fremont type (2009:33). The Claffin-Emerson Expedition from 1928 to 1929 explored this area and primarily focused on identifying caves and rockshelters. As a result, Morss (2009) recorded at least ten rockshelters or granaries with associated maize remains, metates, manos, and occasional clay figurines or pottery within 5 km of the Pleasant Creek canal. Since then, CRM surveys have identified a variety of additional sites. However, while these investigations discovered no large village sites to date, sites associated with Fremont habitation or use occur in definite clusters along drainages. These clusters occur along Tantalus Creek, where Pleasant Creek meets South Draw about 12 km northeast of the canal, as well as along the junction of Oak Creek and Bear

Canyon about 8 km to the southeast (Figure 2). A background lithic scatter occurs across the immediate area surrounding the canal and irrigated field, while fragments of ground stone also occur frequently between the east end of the canal and north end of the field area. Some evidence of significant deposition and subsurface hearth features to the north of the field area suggests that additional sites associated with habitation and possible use of the irrigation feature may remain unidentified.

The Fremont archaeological culture occurs throughout most of Utah within the eastern Great Basin and northern Colorado Plateau. Earliest indications of the culture pattern appear around A.D. 0, and while most settlements appear abandoned by A.D. 1350, some peripheral sites date as late as A.D. 1500 (Madsen and Simms 1998). The earliest maize remains in Utah come from the Elsinore burial site, which dates between 150 B.C. and A.D. 0 (Simms 2008:180; Wilde and Newman 1989). This evidence of early farming predates a definitive Fremont period that occurred after the introduction of ceramics, the foundation of village sites, and a marked increase in site density between A.D. 400 and 1350 (Wilde and Newman 1989). Common distinguishing material remains of Fremont sites include large trough metates, distinctive coiled basketry, grayware pottery, a variety of storage features, and a strain of 14-rowed corn known as Fremont Dent (Adovasio 1979; Aikens 1967; Madsen and Simms 1998; Marwitt 1970).

Archaeological evidence indicates the Fremont exploited a broad range of resources, including high ranked plant and animal foods as well as labor-intensive seeds and domesticates (Barlow 1997; Janetski and Newman 2000; Talbot and Richens 1996). Investment in maize varies geographically and temporally within the Fremont region and researchers have used assumed patterns in maize reliance to classify distinct segments of

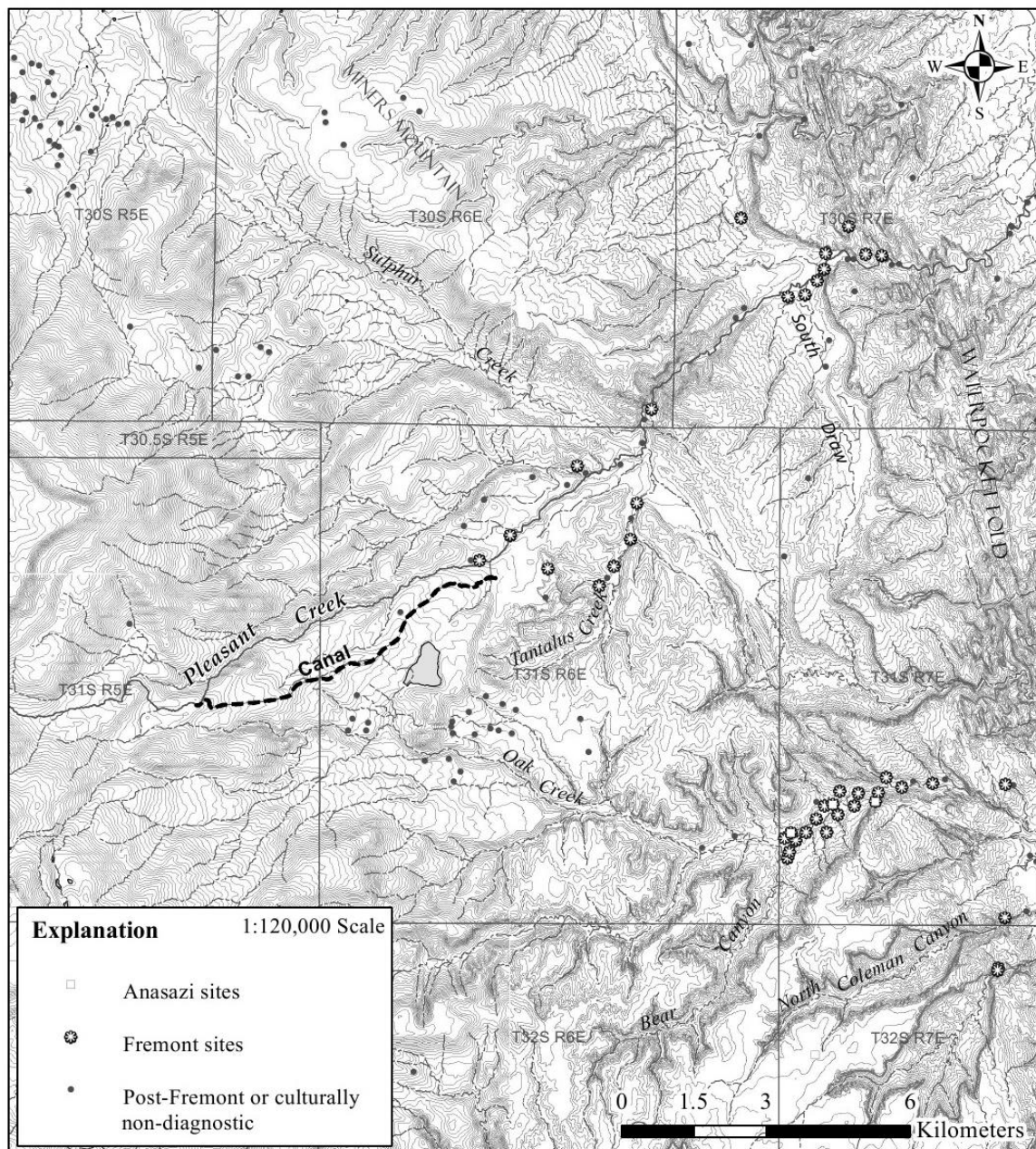


Figure 2. Recorded Sites Surrounding Pleasant Creek

the Fremont population (Aikens 1972; Madsen 1979; Marwitt 1970). However, the mixed economy concept as well as explanations of subsistence and culture resulting from oversimplified definitions of foraging or agricultural systems does not appropriately convey the behavioral implications of the Fremont archaeological record. Resource intensification, a process involving increased time or labor investment in a growing array of subsistence opportunities (see Bird and O'Connell 2006), remains a vital concept to Fremont interpretations. Subsistence variability results from competing selection pressures, and Fremont intensification shows exploitation of many alternative strategies at one time (Madsen and Simms 1998; Simms 2008). Material correlates of investment and causes for intensification offer a basis for conclusions about Fremont economy, agricultural investment, mobility, and social organization.

Fremont irrigation represents one of several intensification strategies. Evidence of Fremont irrigation remains limited, but the practice most likely occurred throughout the culture area where suitable (Gunnerson 2009:138). For instance, locals first showed Morss (2009) the irrigation feature along Pleasant Creek in 1926. Early settlers identified prehistoric irrigation ditches at Brush Creek northeast of Vernal, west of Ferron near central Utah, and Nine Mile Canyon on the Tavaputs Plateau (Gunnerson 2009; Spangler and Spangler 2003). Archaeologists also discovered irrigation ditches at the Steinaker Gap site north of Vernal, and in Gooseberry Valley near Nawthis Village (Metcalf and Larrabee 1985; Talbot and Richens 1996). To date, research has not explored the nature of investment involved with Fremont irrigation. However, other processes and features of Fremont culture reflect intensification and agricultural investment, as well.

*The Path of Investment.* Conditions and processes leading to the development of



the Fremont culture pattern began hundreds of years prior to the crystallization of the Fremont complex. An extended period of aridity ended with the return of a cooler, wetter climate at the beginning of the Late Holocene around 5000 to 4500 B.P. (Grayson 2011). The change in effective moisture, as well as the northward migration of piñon after 6000 B.P., contributed to a rise in population density marked within the Great Basin and California as an increase in the number of archaeological sites across a variety of environmental zones (Grayson 2011:313-314). Resource intensification accompanying population growth is a significant process that occurred within the Great Basin and neighboring regions during the Late Holocene (Kelly 1997:35; Roth and Freeman 2008; Simms 2008; Upham 1994:128). Intensification beginning after 4500 B.P. across the Great Basin manifests as an increase in material remains such as storage features and greater investment in foraging technology (Bettinger 1999). At roughly the same time, foragers in the American Southwest begin cultivating maize (Diehl 2005). The trend toward concentrated investment in both the American Southwest and Great Basin continued especially after 2000 B.P., a period also marked by early evidence of farming in Utah and preliminary traces of the Fremont culture pattern (Bettinger 1999; Diehl 2005; Wilde and Newman 1989).

Archaeologists often attribute the rise of agriculture in Utah to diffusion from Basketmaker II (BMII) cultures in the American Southwest (Talbot and Richens 1996). BMII represents a population of pre-ceramic agriculturalists distinguished by geographic variability in material culture from east to west that also utilized irrigation (Mabry 2008; Matson 1999). Barlow's (1997, 2002) caloric comparison of Fremont maize agriculture to hunted and collected wild foods shows that dry or rainfall maize farming was

economically comparable to collecting low-ranked wild seeds. Therefore, once the idea or means of farming reached the northern Colorado Plateau, the Fremont would have been most likely to farm where the abundance of high-ranked wild foods was limited (Barlow 1997, 2002).

Within a context of population growth, competition, and intensification, farming represented an extension of a strategy already focused on maximizing resources. The distribution of irrigation might also directly correlate with the spread of maize agriculture out of the American Southwest (Damp et al. 2002; Talbot and Richens 1996). A suite of productive maize varieties plus the additional engineering knowledge of irrigation could have influenced early decisions to adopt or transfer maize farming to new areas amidst population and resource stress. For instance, Steinaker Gap in the Uinta Basin includes some of the earliest dates for Fremont farming, as well as one of the few examples of prehistoric irrigation (Talbot and Richens 1996). Agricultural intensification among the Fremont occurred amidst a landscape of full-scale resource exploitation but variable agricultural investment. Archaeologists have tried to understand Fremont agricultural investment in several ways. For instance, storage features and diet suggest agricultural investment.

*Investment through Storage Behavior.* Storage features provide several benefits in return for time and energy spent in construction. Such features provide a place to keep materials and food cool and dry, and protected from spoilage or theft. Storage allows farmers to preserve a surplus harvest and a seed supply with limited risk of premature germination (Lindsay and Loosle 2006; Wills 1988:449,477). Additionally, short- and long-term storage represents a strategy to cope with periods of resource scarcity or

unpredictability (Winterhalder et al. 1999). Preservation of surpluses eases subsistence variance and potentially increases the value of additional effort expended on farming and storage construction (Gremillion 1996). Finally, storage influences land use and mobility as investment in caching reflects intent to reoccupy a particular locality or a decreasing need to relocate (Wills 1988:467; Winterhalder et al. 1999:337; Yoder 2005). While often associated with agricultural sedentism, storage features appear before the onset of domesticated food production and sedentary villages (Wills 1988:446). Degrees of mobility persist even among groups that rely rather heavily on domesticated crops, but storage features do suggest the existence of a “seasonally repetitive pattern of movement around a particular locality on an annual basis” (Wills 1988:459).

The practice of material caching and food storage becomes evident in the Great Basin and northern Colorado Plateau archaeological record after 4500 B.P., before the introduction of agriculture (Bettinger 1999; Talbot and Richens 1996:178). Early shallow subsurface earthen pits used to store tools, raw material, and food, occurred in caves, rock shelters, and some open residential sites while slab- or rock-lined pits appear more frequently after 2000 B.P. (Bettinger 1999:67). Fremont storage between 2000 and 1000 B.P. appears as bell-shaped storage pits and slab-lined cists associated with habitation structures (Bettinger 1999; Madsen and Simms 1998). This type of storage remained in use throughout the Fremont period around the Great Salt Lake, the Uinta Basin, and the Great Basin-Colorado Plateau transition zone (Lindsay and Loosle 2006; Madsen and Simms 1998; Yoder 2005). Around 1000 B.P., masonry or mud storage features such as above-ground bin structures at habitation sites or isolated granaries in rock shelters or cliffs become dominant across the Colorado Plateau and transition zone (Madsen and

Simms 1998:297-298). The size of these surface structures increase through time, ranging from an average area of 0.8 m<sup>2</sup> initially to almost 6 m<sup>2</sup> in later Fremont times (Yoder 2005:54). In some unique circumstances like the Paragonah site, large surface bins ranged from 9 to 26 m<sup>2</sup> in size (Yoder 2005:69-72). In addition to subsurface storage techniques decreasing through time, subterranean storage size also decreases as surface storage size increases, possibly indicating greater reliance on maize and reduced mobility (Yoder 2005:58).

Researchers have used evidence of maize storage among the Fremont to indicate reliance on agriculture (Lindsay and Loosle 2006; Marwitt 1970; Talbot and Richens 1996; Yoder 2005). A comparison of associated farming and storing investments quantifies a connection between the correlated activities. Anthropological studies informed by biological observations of animal storage behaviors indicate that below ground features remain associated with higher mobility more than surface structures (Barlow 2013; Lindsay and Loosle 2006; Winterhalder et al. 1999). Marwitt (1970) initially proposed that the presence of surface storage features, in particular, reflect farming commitment and sedentism at Fremont sites while Lindsay and Loosle (2006) argue that subsurface pits also represent a significant labor investment indicative of cultigen reliance and reduced mobility, if not sedentism. As indicated by both conclusions, storage technique may reflect types of mobility and settlement associated with maintaining and protecting cached goods (Madsen and Simms 1998:299-300; Spangler 2013).

Variability in storage behavior across the Fremont region may be concomitant with variability in settlement and the potential economic status of maize farming through

time. Madsen and Simms (1998:299) posit that patterns of above ground habitation storage and isolated granaries may reflect a strategy of switching between more sedentary village life and mobile foraging. Overall, Yoder (2005:58-59) concludes that changes in Fremont storage behavior reflect a general reduction in mobility, increased population growth, and an increased dependence on farming through time.

Detailed studies of storage from the Tavaputs Plateau suggest another particular pattern. For example, Range Creek Canyon includes a variety of storage techniques used by farmers over time. From A.D. 400 to 860, small household groups of highly mobile farmers inhabited the canyon and stored food in dispersed caches (Spangler 2013). Between A.D. 950 and 1050, a growing and more sedentary population intensified farming investment and stored food in hidden caches as well as large, remote granaries on cliffs. Sedentism increased and by A.D. 1060, storage strategies shifted away from use of cliff granaries. Spangler (2013:164) interprets the archaeological record in Range Creek Canyon, Nine Mile Canyon, and nearby Desolation Canyon as seasonal occupations of mobile Fremont farmers that moved between multiple field locations and cached food near fields for later use. Other researchers contend that Range Creek's remote granaries did not represent storage secured for periods of abandonment as much as an effort to make any attempt at theft highly visible when the canyon was occupied (Arnold Boomgarden 2009; Barlow and Phillips 2010). The preceding discussion of storage behavior not only sheds light on agricultural investment, but also on changing mobility patterns and population density, matters of context for this study.

*Fremont Diet.* Stable carbon isotope analysis of human remains allows archaeologists to study the dietary contributions of particular plant types. The analysis

helps quantify dependence on maize in farming populations. Different plant species metabolize atmospheric carbon in a distinct way that leads to differential uptake of  $^{13}\text{C}$  to the bone collagen of plant consumers (Coltrain 1993). Uptake processes during photosynthesis distinguish between  $\text{C}_3$  and  $\text{C}_4$  plants; most mid-latitude native plants are  $\text{C}_3$  while maize and many grasses are  $\text{C}_4$  (Coltrain and Stafford 1999; Decker and Tieszen 1989). Carbon isotope analysis of Fremont human remains (Coltrain 1993, 1996) suggests that  $\text{C}_4$  plants, most likely dominated by maize, constituted 60 to 85 percent of the diet at Steinaker Gap, Evans Mound, Backhoe Village, Caldwell Village, and Nawthis Village. These sites all represent large residential centers or smaller “Rancherias,” many of which occur near the Great Basin-Colorado Plateau transition zone (Coltrain 1993). However, similar carbon isotope analyses on a larger sample of remains from the Great Salt Lake area, and not affected by the excavation bias of residential sites, suggest maize comprised 35 to 70 percent of the annual diet (Coltrain and Stafford 1999). The Great Salt Lake remains show that local groups may have relied on a greater diversity of resources, but all areas show that the Fremont relied quite heavily on maize for subsistence, despite suspected periods of short-term variability. In fact, the proportion of maize consumption falls within the range of Ancestral Puebloan diets in which isotope analyses report maize represented 70 to 90 percent of annual calories in the American Southwest (Coltrain et al. 2007; Decker and Tieszen 1989; Hard et al. 1996; Martin 1999; Matson and Chisholm 1991).

The relationship between maize reliance and investment in agricultural labor fluctuated over time and likely in response to a combination of climate, geography, and social influences (Coltrain 1993). Variable investment in agricultural labor might occur

during fluctuations in maize reliance while greater investment may accompany periods of relatively stable maize intake (Decker and Tieszen 1989:43). The breadth of isotope samples from across the Fremont region currently underrepresent a variety of site types, but analysis of the more varied Great Salt Lake burials offers a general chronology of maize reliance for that area. Diets high in C<sub>4</sub> foods increase between A.D. 400 and 800 as the result of consuming maize or C<sub>4</sub>-enriched bison meat (Coltrain and Stafford 1999). The period between A.D. 850 and 1150 indicates highly variable isotopic intake and mixed diets. After A.D. 1150, C<sub>4</sub>-enriched diets decrease during a period marked by changes in annual rainfall that could have made maize farming untenable in the Great Salt Lake environment (Coltrain and Stafford 1999:78). Coltrain and Stafford (1999:77) suggest that dietary variability during the middle stage reflects economic diversity in an area where the costs and benefits of growing maize remained comparable to exploiting wild marsh resources.

The Great Salt Lake isotope studies provide additional information for analyzing the nature of maize reliance and the social implications of investment. Data presented in Coltrain and Stafford (1999) identifies notable dietary variability between individuals living in the same area. This pattern supports the idea of adaptive diversity (i.e. Simms 1986) and could result from variable reliance on maize throughout individual life spans by Fremont focused on intensive exploitation of the environment (Simms 2008:215). While initial studies suggest Fremont in northern regions invested less in agriculture based on the rarity of maize remains and residential bases, a combination of poor preservation and modern development obscures the pattern of investment indicated by estimates that maize constituted as much as 70 percent of the diet (Coltrain and Stafford

1999; Simms 1990). Considering this, a diverse subsistence portfolio does not implicate lack of investment in farming, but that farming represented one of many investments. Lifetime diversity would involve a patchwork of social interactions mediated by mobility, resource availability, and access to those resources.

*Social Organization.* Archaeologists have largely linked interpretations of Fremont social organization to studies of subsistence and settlement variability. In relation to this variability, the Fremont archaeological record appears to represent a mixture of organizational traits. Fremont social landscape likely included a complex array of relationships between hunter-gatherers and farmers as well as between individuals with disproportionate access to or control over resources, religious knowledge, and authority (Simms 2008, 2010). Residential cycling of whole groups or individuals across the landscape and between foraging and farming lifestyles, driven by changes in the availability of resources and fluctuating agricultural productivity, also influenced social structure.

Early estimates of settlement size based on stratigraphic contemporaneity of household structures predicted that Fremont people lived in small, mobile residential groups that repeatedly occupied habitation sites (i.e. Sammons-Lohse 1981). Gunnerson (2009:151) concluded that the largest Fremont villages contained at most a dozen contemporaneously occupied pithouses, while three to six houses were more common. Largely based on this perceived settlement organization, Gunnerson (2009) also suggests that the extended family represented the basic Fremont social unit and that evidence did not support the existence of complex socio-political organization. While it is true that most Fremont village sites result from the accumulation of successive smaller



occupations, the archaeological record does suggest evidence of village sites occupied by larger numbers of people. These include Five Finger Ridge, Paragonah, Evans Mound, and Median Village; however, many more may exist unexcavated or lie obliterated beneath modern urban developments (Simms 2008). The Fremont record then includes evidence of short-term campsites, small dispersed communities or hamlets, and large villages (Simms 2008, 2010). The settlement variability reflects changing circumstances of residential cycling, but may also reflect the foundations of settlement hierarchy.

Talbot's (2000b) analysis of Fremont settlement patterns advocate a hierarchy of habitation sites arising from decentralized settlement organization. This organization may reflect the pattern of social structure. Using the Five Finger Ridge area as an example, and drawing from research done with the Dolores Project (Kane 1986:358), Talbot (2000b:209) describes much of Fremont settlement as a series of dispersed communities. Several pithouse groups or otherwise contemporaneous sites not resembling a tendency toward aggregation represent dispersed communities. These scattered habitation sites, possibly tied to a central organizational hub such as the Five Finger Ridge village site, still likely shared frequent interaction. The lack of formal aggregation may still involve coordination between the organizational center and outlying dispersed communities that requires a significant level of structure, influence, and power to navigate. Labor organization and resource sharing may have regularly occurred between groups smaller than the entire village, occurring between neighbors and kin of dispersed communities (Cordell and Plog 1979:417).

Janetski and Talbot (2000) recently examined the Fremont archaeological record for social organization using indicators such as architecture, mortuary practices,

settlement patterns, craft specialization, and evidence of suprahousehold interaction. They conclude that architecture and mortuary patterns suggest social differentiation. In particular, house size and location reflect a concern for social relationships while several features at Five Finger Ridge may also indicate central places instrumental for aspiring leaders. The authors also note, as did Gunnerson (2009:157), some evidence of intercommunity interaction in areas of clustered habitation sites. These clusters could reflect the interaction between several extended family groups, indicating multiple levels of social organization. In some cases, storage behavior may also imply social organization type. For example, Barlow (2013) explains that investment in caching behavior should occur among residentially mobile small bands whereas larder hoarding occurs among foragers and farmers living in extended, corporate family groups residing near agricultural fields.

Scholars infrequently discuss Fremont social organization in terms of recognized social models other than the egalitarian ideal of hunter-gatherers. However, Barker (1994) proposed that the organization of Fremont farmers could reflect a system of sequential hierarchy. Limitations of available data on the role of maize in Fremont diet, the specific uses of storage structures, and a better knowledge of village site demographics rendered Barker's (1994) analysis inconclusive but plausible. Significantly more data is available now to better address how well the Fremont pattern might fit with models of social complexity. Simms (2008:221; 2010) also suggests a model of sequential hierarchy or heterarchy for Fremont communities. Authority may have remained decentralized and loosely ranked, but clear definitions developed for status, group membership, and social roles. Such a system would involve considerably fluid

definitions of power and leadership, and likely occurred frequently among groups in the analogous American Southwest (Hegmon 2005; Simms 2008; Vivian 1989).

### *Irrigation Technology*

Broadly defined, irrigation represents the “artificial application and distribution of water to otherwise dry lands in order to facilitate cultivation” (Doolittle 1990:12). Crop irrigation incorporates several technological methods of water distribution. For instance, farmers can hand-irrigate fields by filling pots from a nearby water source or small artificial wells (Flannery et al. 1971). Farmers may also irrigate fields by diverting slope runoff or seasonal drainage flows to fields or reservoirs using weirs, ditches, rock alignments, and rock dams (Mabry 2005). Canal irrigation involves the diversion and transport of water from a perennial spring, stream, or river by means of gravity flow through artificially constructed conduits or canals (Doolittle 1990:12; Mabry 2005:127). While these different techniques may result from variable ecological and socio-political circumstances, scholars also suggest that individual methods of irrigation develop from cumulative technological change in which the simplest and least demanding technological investment precedes large, complex technologies (Boserup 1965; Doolittle 1990). Regardless, the extent and complexity of an irrigation system reflects different investment levels that have implications for the efficiency of maize agriculture and the social organization of irrigators.

Elements typically associated with prehistoric irrigation systems include the headwater, canal, and fields (Doolittle 1990). The water source, as well as weirs, diversion dams, storage dams, or floodgates represent potential headwater features while

canal elements may consist of a main take-out canal, lateral branch canals, distribution canals, and head gates. Irrigators also use field features such as distribution canals, drainage ditches, water spreaders, bunds, or terraces (Doolittle 1990:13). Current archaeological evidence from the Pleasant Creek project site includes the main canal only. Nevertheless, agricultural labor at this site would have included main canal construction with several take-outs, canal maintenance, field tasks (i.e., land clearing, weeding, and harvesting), and harvest processing. The overall cost of labor, as well as the complexity of labor organization, escalates with the total number of features involved in a given irrigation system.

Irrigation canal characteristics convey information about the engineering capability of ancient farmers, water flow properties, and canal capacity. Investigating these characteristics helps to understand investment in irrigation technology, as well as the effect of irrigation on crop production. Natural forces associated with local environmental conditions influence channel hydraulics. For instance, seepage, evaporation, run-off, and percolation contribute to water loss associated with conveyance and field application. Depending on the canal material and size, nearly 40 percent water loss could occur during conveyance (Farrington 1980). Together, environment, channel design, and water demand influence overall canal output.

Factors affecting the rate of seepage include permeability of canal soil, depth of water, area of the wetted area, flow velocity, and siltation (United States Department of the Interior, Bureau of Reclamation [USDI, BOR] 1968). Many societies developed labor-intensive methods of lining irrigation canals to combat seepage losses, often lining channels with stone slabs or a clay layer (Busch et al. 1976:531; Doolittle 1995:309;

Ortloff et al. 1985:78). However, unlined earthen canals like the one at Pleasant Creek occur commonly throughout the American Southwest and Mexico (Damp et al. 2002; Doolittle 1995). The Food and Agriculture Organization (FAO) estimates that unlined irrigation canals experience between 20 to 30 percent loss of canal flow due to seepage (Tanji and Kielen 2002). The FAO further breaks this loss down by soil type. For unlined canals in sandy soils, like those of the project area, seepage losses may amount to 8 mm/day or 0.93 liters/second/hectare (Brouwer and Heibloem 1986). In addition to canal width and depth, environmental variables also influence evaporation rates. Benson (2011a:11) reports that areas of the semiarid American Southwest typically experience water evaporation at 5 to 8 mm/day (0.58 to 0.93 l/s/ha). Busch et al. (1976:534), however, calculate that seepage accounts for only three to four percent water loss, while evaporation loss may be as low as 0.4 to 0.9 percent depending on canal size and normal flow conditions.

While natural siltation processes may work to reduce seepage over time (Busch et al. 1976; Iqbal et al. 2002), aspects of canal design also serve to counteract inefficiencies of unlined channels. An appropriate gradient, for instance, prevents excess evaporation, seepage, or erosion by regulating the velocity of channel flow (Busch et al. 1976). According to Israelsen and Hansen (1962:84), the maximum velocity permissible in an earthen canal (lacking considerable quantities of gravel or cobbles) without producing significant scour is 1.14 meters/second (m/s), while a hardpan soil can withstand up to 1.8 m/s.

The preceding discussion identifies numerous factors that influence the overall success of an irrigation canal. Each of these factors serve as limiting parameters for

irrigable area and yield volume. A variety of human decisions and environmental factors complicate the process of modelling costs and benefits, but the range of limitations sets parameters for generalized behavioral expectations (i.e., Smith 1983). Mathematical equations help to establish maximum and minimum values for the productivity of irrigated maize at the Pleasant Creek site. Irrigation specialists employ several basic equations to calculate channel hydraulics. The Manning equation, for instance, calculates maximum water velocity for uniform flow conditions:

$$V = (1/N)R^{2/3}S^{1/2}$$

where  $V$  represents velocity in meters per second,  $N$  is an empirical coefficient representing channel roughness,  $R$  denotes hydraulic radius (channel cross sectional area divided by wetted perimeter), and  $S$  indicates slope of the canal bottom (Busch et al. 1976; Farrington 1980; Masse 1981). A number of researchers, including Manning, have experimentally derived coefficients of roughness for a variety of channel types. The  $N$  value for earthen canals ranges between 0.015 to 0.050 depending on canal straightness and the presence of vegetation or rubble along channel beds (Farrington 1980; Masse 1981). The Pleasant Creek canal likely operated with a coefficient similar to 0.025, recommended for winding earth and gravel channels (Farrington 1980:291). Cross sectional area ( $A$ ) for parabolic, saucer-shaped canals, like the features identified at the project area, proceeds from the following equation in which  $T$  equals top width of a channel cross section and  $y$  represents channel depth (Howard 1993):

$$A = \frac{2}{3}Ty$$

$$\text{And wetted perimeter: } P = (T/2)[1+x^2 + 1/x \ln(x + 1 + x^2)]$$

In which  $x = (4 \times \text{channel depth})/\text{channel width}$ . Finally, flow rate or discharge (Q) in cubic meters per second results from multiplying cross-sectional area by velocity ( $Q = AV$ ).

Canal discharge represents the amount of water capable of passing through a given channel. The equation presented here measures the maximum canal capacity. However, ethnohistoric observations suggest that actual canal discharges represent only 25 to 50 percent of the maximum capacity (Howard 1993:289; Mabry 2002:193). Erosion and siltation influence canal capacity over time. Farmers may also intentionally limit water-flow through headgates or diversions, especially if labor availability constrains the maximum farmable area. Additionally, farmers might intentionally over-build canals in anticipation of maintenance issues and declining capacity over time (Mabry 2002).

### *Irrigation Labor Investment*

Time investment in labor indicates societal priorities and possible motivations for subsistence change or intensification. The costs of any technology result from relative time investments taken at the expense of time spent on some other task or technology (Ugan et al. 2003). These kind of opportunity costs rise with increasing time spent in one activity because other opportunities with comparable benefits will become more valuable (Gremillion 1996). A primary objective of this research is to compare the costs of irrigation to dry farming in order to understand the relative value of irrigated maize. The most straightforward expression of irrigation costs lies in determining the amount of labor involved. Total costs considered here involve construction and maintenance of the canal and intake structures, as well as field preparation, harvest, and harvest processing.

*Canal Construction.* Archaeologists and anthropologists have approached prehistoric labor, such as that necessary for irrigation work, through a variety of ethnographic and experimental observations. For example, labor associated with soil-moving activities informs our understanding of irrigation canal construction. Erasmus (1965) staged digging experiments with local men in Sonora, Mexico in order to understand the time required to excavate and carry dirt and rock. He reported that men using wooden digging sticks could excavate about half a cubic meter of dirt per hour (Erasmus 1965:285). Other experimental or ethnographic studies report actual canal excavation rates between 1 and 8 m<sup>3</sup> per person-day, assuming a five to eight hour day (Billman 2002; Mabry 2008; Ortloff et al. 1985; Woodbury and Neely 1972). Different soil types, rock content, worker experience, or digging technique explains the range of labor rates for digging with simple hand tools (Billman 2002; Mabry 2008).

*Maintenance.* Irrigation labor includes more work than that incurred by constructing main take-out canals. Maintenance represents a significant investment because dynamic hydrologic and geologic forces constantly influence the operation of an irrigation system. Maintenance work involves both field distribution features and main intake canals while individual tasks include those done every year, emergency repairs resulting from episodic conditions that threaten canal operation, or preventative measures to resolve continuing maintenance issues (Skogerboe and Merkley 1996:13). According to observations from the early historic contact period of the American Southwest, canal maintenance occurs in the early spring before planting and requires cutting off water flow, draining the canal, repairing diversion dams, removing vegetation and debris, repairing embankment breaches, and cleaning out canal sediments (Ford 1992; Woodson



2010:31). The costs of maintenance are significant because they represent recurring labor investments unavoidably related to the overall use-life of an irrigation system.

For the most part, reports on time spent in irrigation system maintenance come from ethnographic analogy (Farrington 1980; Ford 1992; Hastorf 1993; Hunt 2000; Mabry 2002; Woodson 2007). From his work with ancient irrigation networks in the Peruvian Highlands, Farrington (1980) estimates annual maintenance accounted for one day per kilometer of canal. Ford (1992) reported historic irrigators at San Juan Pueblo, New Mexico spent four, 10-hour days a year maintaining canals, while Doolittle (1984) observed in Mexico that canals required one to two days of maintenance after each flood event. Based on similar ethnographic observations from the American Southwest, Woodson (2010:31) reports that annual maintenance would usually take one to two weeks, while the most typical communal efforts accomplish maintenance repairs in four to seven days. These studies rarely quantify maintenance obligations in any other way than representative time commitments; however, Woodson (2010:143) reports the typical sediment accumulation within a canal in a single year ranges between one-fourth and three-fourths of the canal volume, with one-fourth representing the most typical sediment accumulation.

*Field Labor.* Canal construction and maintenance labor represents the primary costs that set irrigated maize agriculture apart from dry farming. Additional agricultural tasks common to both strategies include field preparation and maize processing. Field labor tasks include clearing land, planting seeds, weeding, and harvesting using simple hand tools while overall field investment for dry or irrigated plots varies with community type, climate, vegetation, soil type, and elevation (Barlow 1997; Sanders and Nichols

1988; Welch 1996). Barlow (1997) compared ethnographic data from subsistence farmers living in different ecological zones of South and Latin America to evaluate levels of field investment analogous to prehistoric Fremont agriculture. Agricultural investment among the Fremont most likely fluctuated from year to year depending on ecological circumstances, prevailing climate regimes, and available opportunities for less-costly resources. Barlow (2002:80-81) found that dry-farming Fremont communities likely operated between a “slash and burn” (100 to 250 hours/acre) and “typical subsistence” (300 to 500 hours/acre) level of field investment. Barlow’s (1997) labor estimates include just dry farming strategies with field investments that would remain much the same with irrigated farming; however, weeding, harvesting, and field maintenance costs could increase.

Additional ethnographic accounts provide information about irrigated field investments. According to experimental maize cultivation in Mexico, irrigated fields located in sandy loam soils at elevations generally above 7,000 feet required an investment between 230 and 382 hrs/acre (Logan and Sanders 1976:44). These figures represent work done with stone and wood tools and include some annual canal-related tasks as well as field labor, but do not include harvest processing. Hastorf (1993) reports that part-time maize farmers in the Peruvian highlands spent an average of 105 days per hectare in agricultural field work, including irrigation. While she does not suggest an average workday length, up to 385 hours per acre could result from nine-hour workdays (a convention adopted by Barlow 1997:114). Hopi farmers in northern Arizona report spending about four hours per acre hoeing floodwater fields and working at least 100 hrs/acre clearing vegetation (Dominguez and Holm 2005). As with dry farming,

information about irrigated field labor reflects discrepancies in specificity or tasks involved and often does not include reports of associated productivity (Barlow 1997; Mabry 2005:136).

*Processing.* Harvest processing costs represent an additional and significant farming expense. In fact, Barlow (1997:133) concludes that post-harvest processing time may represent as much as 45 to 90 percent of all time spent farming annually. This fact remains true for alternate farming strategies and irrigation technology directly influences harvest yield and associated processing needs. Barlow's (1997) ethnographic research and grinding experiments led her to use a 43.55 hours/bushel (1.8 hours/kg) processing rate in her return rate estimates. Additionally, Barlow (1997) concluded that increased time investment would only enhance agricultural return rates if processing efficiency also increased. Therefore, processing time significantly conditions the overall return rate of maize, especially for farming strategies with high yields.

#### *Crop Productivity and Irrigation*

Irrigation can enhance both the heartiness of crop plants as well as the total number of healthy plants in a given field. Water application also directly affects crop yield by influencing farmable area. Because archaeologists (i.e. Busch et al. 1976) have found that the geometric characteristics of irrigation canals remain more important to capacity than forces of evaporation and seepage, we may infer that prehistoric irrigators engineered canals to fit anticipated water demand. This assumption allows researchers to determine a realistic farmable area from the hydraulic variables of irrigation systems. An operational irrigation principle maintains that every hectare requires a flow rate of about

one liter per second (Mac McKee, personal communication 2012). This standard facilitates calculation of land affected by an irrigation system of given capacity.

Ultimately, heartiness and farmable area represent the best measures of effectiveness between irrigation and dry farming.

Agricultural experiments and cross-cultural observations conducted during the late nineteenth and twentieth century throughout the American Southwest describe maize productivity under different farming technologies, climates, and elevations (Arbolino 2001; Barlow 1997; Bradfield 1971; Castetter and Bell 1942; Ford 1992; Herhahn and Hill 1998; Logan and Sanders 1976; Mabry 2005). For example, Herhahn and Hill (1998:475) estimate potential maize yield for irrigated floodplain soils of New Mexico at about 710 kg/hectare. In addition, Logan and Sanders (1976:44) compiled experimental data from irrigated maize in the semi-arid Basin of Mexico and report that 75 to 113 days of labor produced about 1,000 kg/hectare. However, while crop yields vary most with farming technology, Arbolino (2001) concludes that elevation strongly conditions productivity within similar farming systems given that altitude influences rainfall, temperature, and growing season. Arbolino's (2001:294) reported ethnohistoric maize yields from the northern American Southwest for irrigated fields located above 5,500 feet elevation produced an average of  $1,167 \pm 360$  kg/hectare (Arbolino 2001:294; Mabry 2005:133).

Alternatively, Diehl and Waters (2006:84) infer from archaeological cob remains that maize grown during the Early Agricultural period of the American Southwest produced small cobs not likely ever to yield more than 300 kg/hectare when irrigated. Mabry (2005) uses similar ethnographic and experimental yield estimates to calculate

crop productivity for the early communities of Las Capas and Los Pozos in Arizona; however, he reduces ethnographic yields by two-thirds to reflect lower productivity of prehistoric maize varieties. Even with Diehl and Waters' (2006) recommendation, Fremont maize likely proved more productive than early American Southwest varieties due to the emergence of dent maize adapted to higher elevations of the Colorado Plateau (Gunnerson 2009; Winter 1973; Winter and Wylie 1974).

### *Irrigation and the Organization of Society*

Historians and anthropologists traditionally view irrigation as a major shift in subsistence strategies, which significantly affects human lifestyles (Steward 1955; Wittfogel 1957). Intensifying agricultural production with water control features may cause changes to fundamental socio-political relationships. Irrigation enables higher crop yields and a means of coping with poor environmental conditions; however, water management incurs both physical and social costs. Physical costs include labor, time, and a commitment to place (Howard 1993; Mabry 2002; Scarborough 1991). Social costs include labor organization and water allocation, as well as time spent on conflict resolution or ritual obligations associated with water management (Hunt and Hunt 1976). The social impact of such investment results from the managerial requirements of irrigation labor, uneven distribution of irrigable land and the resulting productivity, or authority emerging from the control of water distribution (Davies 2009; Wittfogel 1957).

Previous discussions about irrigation and society have shown that socio-political complexity varies among irrigating groups but rarely represents an inevitable circumstance of water management (Adams 1971; Davies 2009; Geertz 1972; Hunt 1988;

Hunt and Hunt 1976; Leach 1959; Lees 1994). Debate over the relationship between irrigation and the development of complex society often fails to identify correlates of social complexity in the archaeological record. Using irrigation system size as a proxy for “scale of investment” and managerial complexity among prehistoric societies, for which we have little conclusive evidence of socio-political affiliations, may provide some insight into ancient society but not a complete picture. The magnitude of agricultural investment cannot explain permutations of cultural development on its own.

Nevertheless, the range of investment evident in modern or ethnographically known societies offers up analogies of principle for evaluation against the archaeological record. I explore examples here that review societies with different means of distributing authority and decision-making control. The examples explore more than a simple dichotomy between egalitarianism and complexity by including a range of socio-political systems between complex state-level societies with centralized power, corporate organization, and systems governed by local or restricted authority. These examples provide a basis to estimate the Fremont social organization associated with an adaptive strategy of irrigation.

*The Hydraulic State.* Wittfogel (1957, 1971) and Steward (1955) advocated the “hydraulic hypothesis,” in which the organizational structure of irrigation establishes societies that differ in socio-political complexity from societies based on dry or rainfall farming. While Wittfogel (1957) constructed an argument for how irrigation contributed particularly to the development of the despotic state, he also acknowledged different types of agricultural societies in which irrigation management provided the means of political power. Ultimately, the “hydraulic hypothesis” models a variety of society types

based on the level of integration between political power and agricultural management, as well as the degree of centralized power over irrigation. The fundamental concept maintains that the managerial requirements developed from irrigation technology represented a basis of authority and played an instrumental role in the growth of early complex social hierarchies. Wittfogel (1957) attributed the resulting complexity to three primary characteristics. The first characteristic demands intensified cultivation. Second, “hydraulic society” incorporates a noted division of labor between preparatory activities of irrigating and basic farming tasks, and the societal implication becomes more significant with the greater amount of time devoted to those preparatory tasks. The last characteristic involves large-scale cooperation under a well-defined leadership network.

Broad assumptions about irrigation as a lone explanatory mechanism for the development of complex societies typify interpretations of the “hydraulic hypothesis” (Erickson 1993; Hunt 1988). Most critics also identify an important weakness of Wittfogel’s hypothesis as a lack of archaeological or ethnographic evidence supporting consistent development of significant irrigation systems prior to state formation, often signified archaeologically by the appearance of population aggregation, monumental architecture, and universal iconography (Adams 1971; Billman 2002; Earle 1980; Hunt 1988; Lees 1994; Mitchell 1973; Leach 1959). The same sources also provide positive examples of irrigation systems managed in the absence of a centralized authoritarian government. Mitchell (1973) notably recommended that the “hydraulic hypothesis” does not describe the implications of large-scale irrigation, but instead models the potential development of societies within arid or semi-arid regions that do manage irrigation technology through a centralized political authority.

*Decentralized Socio-political Systems.* Anthropological research, particularly in the American Southwest, tends to portray ancient societies in terms of a dichotomy between hierarchical or egalitarian organization (see discussions in McGuire and Saitta 1996; Rautman 1998). However, there are different paths of cultural development and many societies exist between these classifications. Alternative organizational strategies that emerge from egalitarian societies include corporate groups, heterarchies, or sequential hierarchies that produce socio-political systems of varying scale and complexity (Hayden 1990; Hegmon 2005; Vivian 1989). Corporate organization generally deemphasizes individual leaders by spreading more power, developed in a number of ways, across horizontal divisions rather than strengthening vertical divisions of hierarchy. Corporate groups can form through common links between people such as kinship, labor, religious roles, or resource control (Hayden 1990). Heterarchies occur when “each element is either unranked relative to other elements or possesses the potential for being ranked in a number of ways” (Scarborough et al. 2003:67). Sequential hierarchies reflect a fluid system of power in which smaller organizational units band together under a provisional hierarchy when a higher level of consensus is required among the units (Vivian 1989). “Big man” societies fall in this category and represent a system where multiple leaders compete with each other for influence (Hayden 1990). Each alternative social strategy reflects different scales and types of complexity while decentralizing socio-political power and often incorporating some social levelling mechanisms that discourage ostentatious displays of power (Hegmon 2005). Importantly, several different socio-political strategies can operate within a single society. Diversified



organizational structures may outwardly appear less complex, but together represent different adaptive trajectories of an integrated system (Vivian 1989).

Fremont irrigation may have occurred under the auspices of mid-level complexity, such as corporate group organization or a heterarchy-sequential hierarchy. A corporate system of power involves multiple power holders and often discourages exclusionary power such as that found in hierarchical, ruler-centered political economies claiming primary control over economic resources. For example, Davies (2009) describes an irrigation system managed by a communal group in the absence of significant social stratification. Certain East African communities distribute authority to a group of all circumcised males or a council of male elders. The corporate authority represented by these groups enforces participation in irrigation labor by assessing fines in the form of goods or denial of water supplies for individuals that do not contribute. The group also delegates the supervision of maintenance and distribution tasks. To some degree, differential water rights define social privileges and regulate personal accumulation of wealth. Davies (2009) contends that the management of irrigation systems often results in corporate authority when individuals can pursue multiple sources of power including agricultural influence but also personal charisma, accumulated wealth, or supernatural knowledge. Such a system resembles a “big man” society where leaders acquire significance through the control and distribution of knowledge or resources in a way not necessarily related to the accumulation of wealth (i.e., competitive feasting or “fiesta finance”) (Rice 2008).

Cross-cultural examples of irrigation management from the American Southwest provide socio-political analogies applicable to Fremont society. One example comes from

Early Agricultural period forager-farmers. Mabry (2002) suggests that local, small-scale irrigation projects in the Early Agricultural Southwest would have involved multiple levels of community-based organization. For example, communally administered water delivery systems may serve multiple fields considered private household property. Family groups or members of a discrete irrigation community subsisting from a given water system owned, operated, and maintained canals of the Akimel O'odham, Western Apache, and Navajo (Mabry 2008). In these cases, decisions about water distribution and delegation of labor tasks may fall to the authority of a village council, village headman, ditch boss, or a consensus among water-users. Kin-based alliances and religious associations also assume management responsibilities over irrigation in Hopi and Eastern Pueblo communities (Mabry 2008). Notably, the locus of authority for small-scale irrigation in American Southwest communities took advantage of existing socio-cultural relationships governing other means of cooperation and community organization.

*Egalitarian Systems.* Strict egalitarian societies operate with few distinctions of wealth, power, and status, but the characteristics of egalitarianism differ between societies that obtain resources through an immediate-return or delayed-return system (Woodburn 1982). Immediate-return systems, usually found among hunter-gatherers, are characterized by high mobility, small residential group units, flexible group membership, equal access to food and resources, and sanctions on individual accumulation of wealth or power (Woodburn 1982:435-436). However, farming nearly always represents a delayed-return system in which people hold rights over yields or other returns from human labor invested over time. Unless farming investment remains undemanding and unsystematic, effective systems require defined relationships for the transmittal of goods and services,

including pooled labor for the planting, protection, and harvest of agricultural yields (Woodburn 1982). Delayed-return systems may also support egalitarianism in the form of competitive equality. In this scenario, household heads retain a position of authority within their own family or household while competing for equality with other heads through equal exchange of resources among them. As Woodburn (1982:446) states, “keeping up with the Joneses” could mean that each household head starts with an equal opportunity to compete for wealth, power, or prestige.

Irrigation develops in societies of varying complexity and stratification, and the management of these systems grows from social mechanisms that also regulate resource procurement, dispute resolution, or information sharing. Therefore, irrigation technology does not require significant increases in social complexity immediately upon adoption. Cross-cultural studies show examples of irrigation systems managed by relatively small, unincorporated groups. For instance, historical observations of the Pima/Papago culture describe situations where loosely organized groups or small families constructed and managed complex irrigation systems (Woosley 1980:323). Ford (1992) describes annual irrigation efforts accomplished by the ethnographically egalitarian San Juan Pueblo. Owens Valley Paiute also irrigated and tended native plants within a relatively simple social system with small-scale leaders (Eerkens 2009; Lawton et al. 1976). However, irrigation efforts demonstrate a strong correlation between irrigation and some level of power beyond the individual farmer (Earle 1980; Hunt and Hunt 1976; Mitchell 1976; Uphoff 1992:236).

The variety of alternative cultural examples for irrigation management shows that the relationship between irrigation and social complexity is not a one-to-one correlation.

Complexity and irrigation develop together, but independently in many societies where irrigation functions as a component of a broad intensification strategy (Adams 1971; Lees 1994). Sociopolitical mechanisms involved with irrigation originate from and affect other aspects of society. Additionally, irrigators may manage water control tasks separately from the overall power structure (Hunt et al. 2005). For example, multi-leveled power structures like states may exercise differential control over irrigation tasks so that the primary level of government remains uninvolved in most irrigation decisions. Overall, the archaeological record suggests the Fremont did not form state-level societies (Madsen and Simms 1998; Talbot 2000a). Moreover, Woodburn's (1982) analysis leads to the conclusion that Fremont irrigation would have involved communal organization and resource ownership uncharacteristic of a simple egalitarian society.

*Irrigation and Settlement.* Researchers generally link agricultural intensification to increased sedentism resulting from efforts to minimize transport costs and facilitate cooperation among larger groups of people (Adler et al. 1996; Chisholm 1979; Fish and Fish 1994). Water management for crop production requires irrigators to commit to locations of water availability. This commitment involves investments in landscape modification and storage facilities, which require consistent maintenance and protection (Mabry 2008). The distribution of people across the landscape represents both an indicator and stimulus for changes to social structure.

Population aggregation may also influence the degree of centralized authority over water management (Scarborough 1991). However, while irrigation often co-occurs with aggregated settlements, there exists no strict causal relationship between irrigation and aggregation. The strongest correlation seems to be the suggestion that aggregated

communities result from changes in labor organization favoring larger labor groups to support such things as extensive field plantings, water control activities, and field defense (Adler et al. 1996:392; Leonard and Reed 1993). Relatively dispersed communities still manage to construct and maintain irrigation systems while other pressures such as defense, resource competition, or better sharing opportunities may influence population accumulation (Adler et al. 1996; Mabry 2008). Agricultural intensification resulting in productive resource patches, surplus, storage facilities, and farm and field infrastructure all entail a great labor investment regardless of residential organization, but several different forces likely condition any movement to clustered settlement.

In many cases, settlement may reflect the relative degree of social or political organization. For instance, a hierarchical settlement system of smaller sites surrounding a larger, centrally located site reflects centralized organization (Billman 2002). One example of settlement among de-centralized irrigators comes from studies in the American Southwest. Mabry (2008:262-265) describes a model of seasonally differentiated sedentism based around a phenomena of tethered settlement drift. The model, used to describe the Early Agricultural period, suggests that primary agricultural settlements center around the location of water sources and constructed features. Climate, elevation, and local flood characteristics influence the permanence of primary residential sites while populations fluctuate within residential sites seasonally. An agricultural population may cycle between aggregated residential sites and outpost settlements associated with field and canal work depending on the seasonal and spatial organization of agricultural places to which the population remains tethered (Mabry 2008). The

mobility pattern of agriculturalists following this strategy does not resemble strict sedentism, but stems from familiar models of hunter-gatherer mobility (Binford 1980).

Although Mabry (2008) uses tethered settlement drift to describe a society presumably on the fringe of agriculture, similar patterns persist with increasing levels of agricultural commitment. Tarahumara communities in Northern Mexico represent examples of mobile agriculturalists that engage in both logistic mobility and multiple types of residential mobility (Hard and Merrill 1992). Inhabitants move residences to field locations during the growing season, some move during winter months to rock shelters in warmer mid-slope locations near wood resources, and families might move households to a nearby cultural center for several weeks at other times in order to observe celebrations or ceremonies. Logistic trips include men travelling away from the residential base to find other work, as well as individuals or families making day trips to work in closer fields or collect other resources. The Tarahumara system includes multiple residences associated with a variety of field locations, most of which occur within a 5 to 15 km radius (Hard and Merrill 1992). Spangler (2013) hypothesizes that Fremont settlement of the Tavaputs Plateau may bear resemblance to the Tarahumara pattern. At the time of historic contact, the Tarahumara lived in small hamlets, or *ranchos*, consisting of one to 20 households directed to a limited degree by a headman and body of elders (Merrill 1983). The focus of social life centered on maize-beer parties, often organized by farmers to enlist the aid of neighbors for fieldwork or rituals (Merrill 1983). The pre-contact Tarahumara society may have operated as some form of sequential hierarchy with limited corporate government.

*Archaeological Implications of Complexity*. Research supports a link between the size of irrigation systems and social complexity or political centralization (Earle 1980; Mitchell 1976; Netting 1974; Wittfogel 1957). The exact relationship between irrigation investment and the scale of political centralization remains problematic. However, some theories exist concerning group size (work force and population) and levels of political centralization and hierarchy (Earle 1980; Feinman and Neitzel 1984). Cross-cultural studies have shown that overall population size influences social complexity most within aggregations or communities that represent tightly interacting social entities (Feinman 1995). In such communities, any population over 2,500 people should reflect significant organizational complexity while organization type remains highly variable with populations below 2,500. In addition, hierarchical organization does not necessarily characterize dispersed populations of 2,500 people or greater (Feinman 1995:260).

Feinman and Neitzel (1984) statistically analyze ethnographic data from pre-state sedentary populations to determine thresholds at which population size determines necessary administrative levels of society. The authors find positive correlations between maximal community size and administrative levels, such that communities of 100 to 250 people may support one or two administrative levels (Feinman and Neitzel 1984:69). According to Billman's (2002:375) interpretation of their work, political authority rose above that of an informal, ephemeral leadership system with the establishment of formal administrative levels to handle large work force sizes. Communities of one hundred to several hundred people typically support administration by a village chief, headman, or council. Two or three administrative levels may characterize a simple chiefdom supporting one thousand to several thousand individuals while a larger population in the

tens of thousands should support three or more administrative levels and resemble a complex chiefdom or state society. A small, autonomous community or village with community-level political integration represents the alternative to centralized management and considerable social complexity (Billman 2002; Davies 2009; Erickson 1993; Wittfogel 1957).

Few researchers have attempted to model socio-political organization for groups smaller than several thousand. Johnson (1983) considers how group size influences decision-making capabilities and determines optimal group size for reducing administrative stress. He concludes that group sizes of six basal units or more should develop hierarchical group structure as the ability to cooperate becomes more difficult with increasing group size. The conclusion can indicate that a group of more than six individuals (perhaps a single family) will develop a hierarchical order, but also that a group of six or more families may experience cooperative stress without divisions of authority.

Additional characteristics of the archaeological record help to assess evidence of centralized authority. For instance, situations where the population of larger sites exceeds the productive capability of the surrounding site catchment area imply higher levels of authority. Settlement hierarchies exhibiting distinct patterns of site size with small sites clustered around larger ones indicates centralization (Billman 2002). Public and monumental architecture have long represented a defining characteristic of complex and state-level societies. These structures should remain absent from or very limited in size within societies functioning with few administrative levels (Billman 2002).



The framework of functional population thresholds allows the archaeological record to contribute information about centralization and complexity from the size of irrigation systems. Calculations of labor requirements, work force needs, irrigable area, and sustainable population size for the Pleasant Creek site help to define boundaries of socio-political organization if compared to ideas of population and complexity, as well as other indicators of inequality or centralized authority developed through cross-cultural analogies. Initially, cross-cultural studies of irrigating communities indicate a need for communal cooperation and resource ownership uncharacteristic of egalitarian groups. Middle-range societies, for which examples discussed above include corporate groups or heterarchy-sequential hierarchies, involve some aspects of egalitarianism, institutionalized inequality, and a mix of communal and individual power. The mixture of these forces in Fremont society likely varied geographically and through time, but the hypotheses of this research question the general scale of complexity necessary for irrigation at Pleasant Creek.

### *The Economics of Subsistence Change*

Anthropological studies of subsistence change often focus on intensification, defined by Boserup (1965) as the process by which investment of additional energy and time per unit area results in an increase in the total productivity per unit of land. Early on, Boserup (1965) evaluated a long-recognized relationship between population growth and intensification. Relying on population growth as the primary stimulus for agricultural change, she indicates that a growing population cannot produce more food simply by increasing time spent in existing agricultural fields. Populations must either intensify by

adopting technology that increases productivity of existing fields or expand the farmable area (Boserup 1965; Hunt 2000). If population growth determines agricultural intensity, Boserup's model predicts agricultural intensification will only occur if a territory becomes crowded. In addition, small populations should not progress past simple agriculture as long as ecological conditions require that farmers move field locations every couple of years, thus preventing the elaboration of social organization (Boserup 1965). Boserup (1965) also maintains that labor intensification will result in greater productivity but declining efficiency, a trend that will continue unless some change to technology benefits efficiency.

The proposed analysis of Fremont farming efficiency remains rooted in fundamental observations about the nature of intensification. Research objectives aimed at discerning the conditions of irrigation consider factors related to labor or technological investment, productivity and efficiency, and population size associated with investment.

## FIELD METHODS AND DATA COLLECTION

Data required for an economic analysis of Fremont irrigation efficiency comes from several sources. Field survey and test excavations provide the primary data on size and design of the Pleasant Creek irrigation system, information used to quantify labor needs and irrigable capacity. Experimental digging exercises generate a realistic labor rate for calculating the costs of irrigation while a literature search identifies information on field labor and maize processing costs derived from ethnographic studies. Productivity data on irrigated and dry maize, also derived from ethnographic and historic contexts, forms the basis for estimating the productivity of an irrigated plot on Jorgenson Flat, especially when considering local environmental conditions.

### *Survey and Identification*

Preliminary surveys conducted in 2010 and 2011 within the Pleasant Creek study area identified evidence of the irrigation feature reported by Morss (2009) between Jorgenson Flat and Pleasant Creek. The evidence included several sections of possible ditch grade on a roughly two-percent slope connected by sections of natural drainage (Simms and Kuehn 2012; Simms et al. 2012). Additional survey in 2012 focused on identifying the extent of the irrigation channel from intake diversion to field. Field survey began at the diversion from Pleasant Creek and tracked the likely canal route from there.

The project survey mapped a series of shallow channel grades and suspected natural gradient drops used in the system, including possible portions altered by historic diversion from the intake to Lower Bowns Reservoir (Figure 1). Overall, the irrigation system consists of a single transport canal that extends about seven kilometers and drops

just over 1,000 feet in elevation from the head of Pleasant Creek to Jorgenson Flat. Water still runs through the diversion from the intake at Pleasant Creek, modified historically with metal head gates. The water follows a contour to the southeast and drops into natural drainages several times before diverting to Lower Bowns. The area between intake and diversion to the reservoir exhibits multiple incised, abandoned channels that likely result from historic use. Based on the results of field survey and review of the topography, the original canal builders could have constructed about 3 km of the canal length running to Jorgenson Flat with the remaining sections representing natural drainages utilized to reduce initial labor costs.

#### *Test Excavations*

The second stage of field investigation aimed to demonstrate subsurface manifestations of the subtle ditch grade identified during survey. Test excavations focused on an area along the lower reaches of the irrigation feature in a section apparently unaltered by historic development as well as where the surface ditch grade was most discernible (Figure 3). The field crew dug trenches with shovels and a mattock. Test trench profiles were drawn and measured to describe soil and feature characteristics.

Seven test trenches initially dug in 2012 measured 50 cm wide, 2 to 4 m long, and up to 50 cm deep. Each of the seven trenches exposed features showing alternating layers of sand and gravel (Figure 4). In most cases, the top-most feature resembles a shallow and wide saucer-shaped channel while underlying features show earlier saucer-shaped or u-shaped channels. The features range from 100 to 70 cm wide and average 20 to 30 cm deep. Exposed profiles offer preliminary information on channel characteristics. For

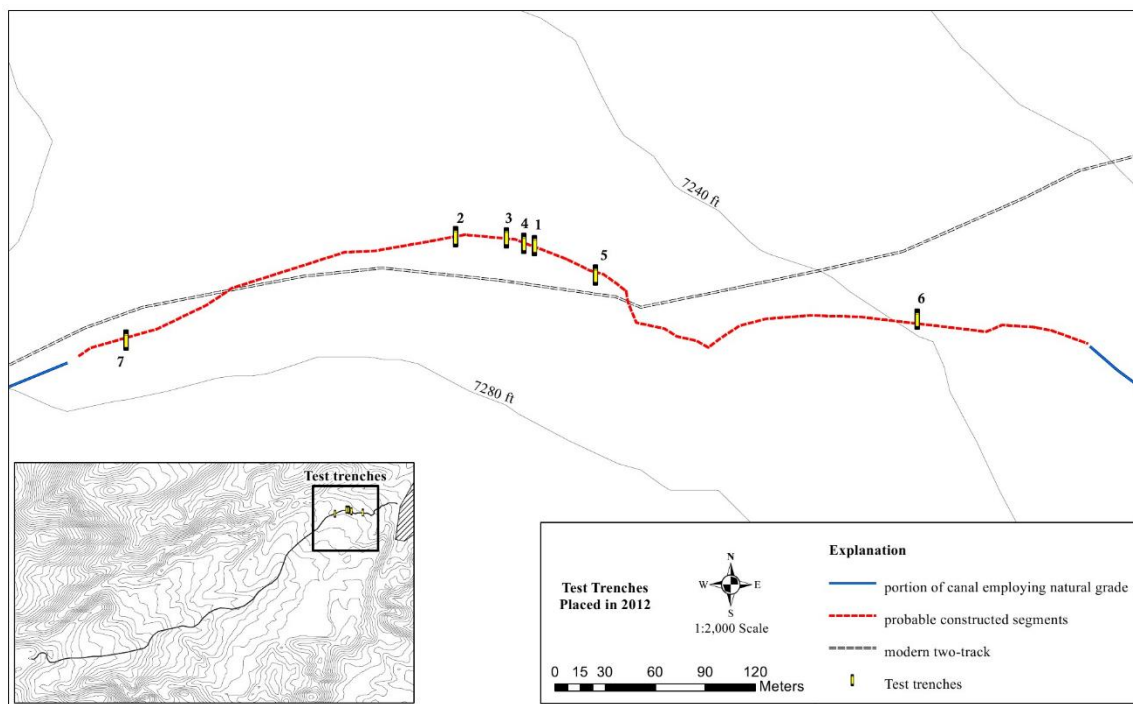


Figure 3. Test Trenches Placed in 2012.

example, Trench 1 shows a later channel intruding upon lower layers, and reflects lateral movement of successive channels over time. Trench 5 shows cross-bedded sand layers and possible unequal deposition at a suspected curve in the system. Fieldwork conducted near the completion of this thesis expanded several test trenches. The larger and deeper excavations revealed at least five episodes of channel modification extending nearly 1 m below surface, showing an accumulation of superimposed channels over a substantial period of time (Figure 5). The deepest features reflect a notably more narrow and trapezoidal profile than the upper saucer-shaped profiles.

In order to assess a possible terminal date of canal use, we sampled a sand layer near the top of the channel features first exposed in 2012. The sample came from one upper u-shaped exposure about 35 cm below surface of Trench 5 and consisted of quartz

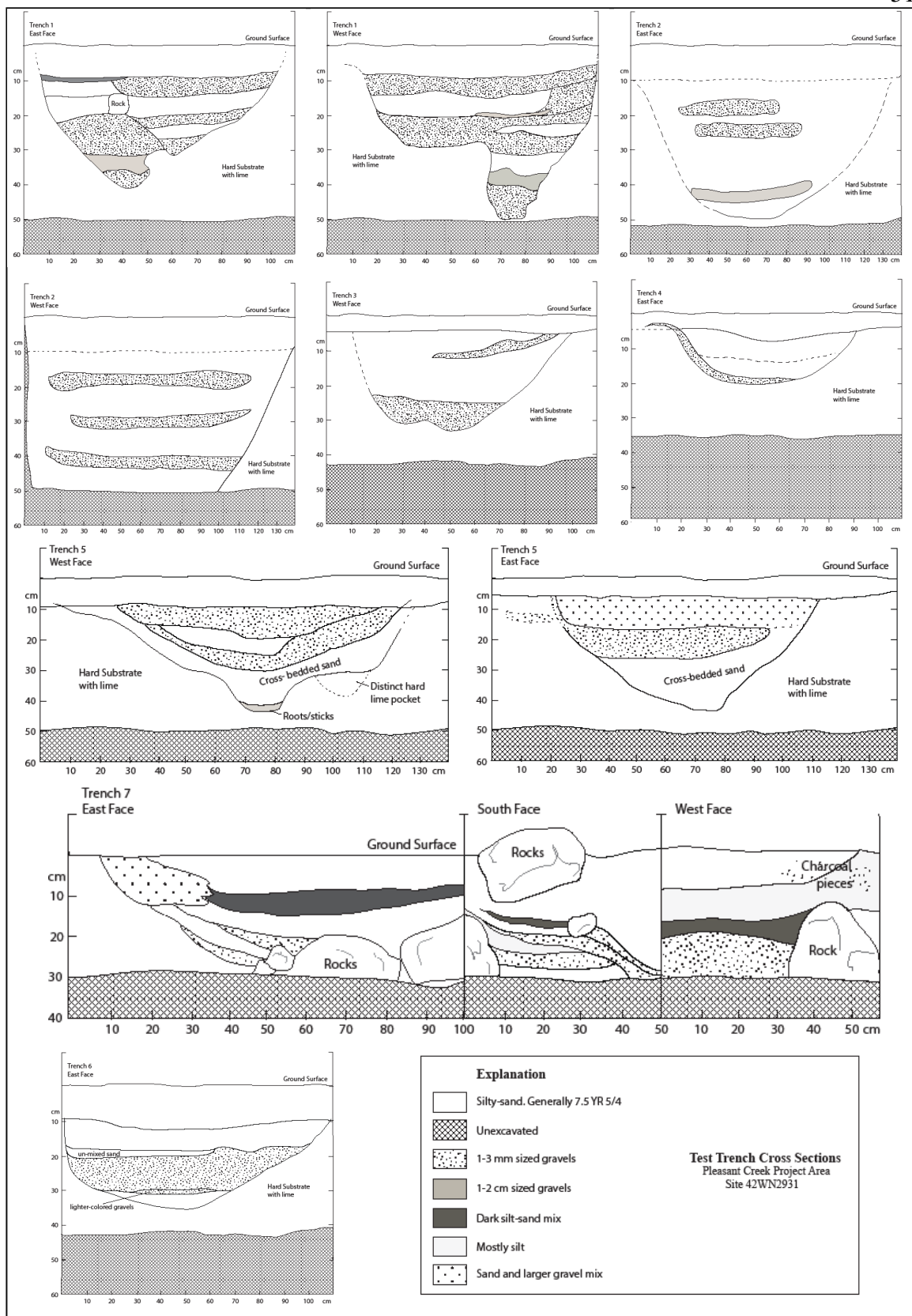


Figure 4. Cross Sections of Subsurface Channel Feature

sands derived from Navajo sandstone. The Utah State University optical stimulated luminescence (OSL) lab processed the sand sample using single-grain methods to control for partial bleaching of sands in alluvial contexts. Analysis returned a date of A.D. 1690  $\pm$  120 (Simms and Kuehn 2012). The successive channel features below the sampled location suggest an origin that may fall within the Fremont culture period, perhaps between A.D. 900 and 1300. The sampled layer may represent terminal fill of the channel after abandonment or possibly terminal use of the channel during an episode of post-Fremont but still pre-Columbian irrigation. Utah State University researchers collected



Figure 5. Expanded excavation profile of Trench 5, east wall. November 2013.

more OSL samples from expanded test trenches in 2013; however, additional dates are not yet available. Future research will better define the channel morphology and chronology of irrigation at Pleasant Creek

### *Experimental Methods*

*Construction.* Experimental labor simulations help to understand the time investment necessary for constructing a complete canal at Pleasant Creek. Experimenters constructed seven ditch segments in 2012 and 2013 to model labor costs using simple tools and manual effort. The experiments included three dry ditch segments, three diversion ditches, and one ditch in wet soil but not associated with diversion. Each ditch placement represented different soil or terrain conditions that influenced the labor rate. Two people dug the sample ditches using wooden digging sticks and a flat shovel tool to remove loosened dirt from the ditch. The digging sticks were fashioned of mountain mahogany branches generally 4 to 5 cm in diameter, 90 to 100 cm long, stripped of bark, and fire-hardened. Initial trials with un-prepared digging sticks revealed that randomly selected branches of appropriate size broke often and were typically less efficient than the treated ones. However, the time and labor investment put into digging stick manufacture is not included as a significant contributor to irrigation labor costs because such tool manufacture tasks were likely embedded in other subsistence activities (Bright et al. 2002; Ugan et al. 2003). Information collected from the experiments includes ditch dimensions, excavated soil volume, general soil type and moisture, vegetation cover, and construction time (Table 2).

The Pleasant Creek site likely involved substantial diversion costs due to the



Table 2. Experimental Ditch Characteristics

Experiment #	Final Dimensions (width x center depth x length in meters)	Wet or Dry	Soil Characteristics
Ditch 1	1 x 0.25 x 3	Dry	Alluvial, fine grained, light reddish-brown silty sand. No surface gravels; vegetation consists of 1-3 cm tall small ground forbs with small roots. More compacted, redder soil occurs at 5-10 cm depth. Weakly developed profile.
Ditch 2	1 x 0.15 x 3	Dry	Medium brown silty loam in the first 5 cm. Roots of grass and lupine anchor a 2-3 cm organic layer that also includes thin pine needle mat. Clayey hard pan occurs at 5 cm depth. Soil includes coarse gravel, palm-sized pebbles, larger rocks 15-25 cm across, and vegetation roots 2 cm in diameter and smaller.
Ditch 3	0.6 x 0.20-0.25 x 1.65	Wet <i>Creek Take-out</i>	Dark alluvial silts. Grass and leaf mat makes up 2-3 cm surface layer. Entire ditch depth intersects root mass of nearby tree. No other soil layers discernible from wet excavation.
Ditch 4	0.7 x 0.25 x 7.05	Wet <i>Creek Take-out</i>	Alluvial sediments along stream floodplain and bank. Dark silts with small and large pebble gravel. Most of the ditch had sparse grass cover at surface. Water level in ditch 3-6 cm at all times
Ditch 5	0.7 x 0.20 x 3	Dry	Fine-grained, light reddish-brown silty sand makes up the first 15 cm. Top-most 2 cm anchored by scattered bunch grasses. Hard pan with large pebbles begins at 15-20 cm depth.
Ditch 6	0.6 x 0.25 x 1.5	Wet <i>Filled reservoir at head of ditch</i>	Fine-grained, light reddish-brown silty sand with a hard pan about 15 cm below surface. Ditch filled with water to excavated bank-full or 5 cm below during digging.

number of times canal builders would need to capture fast-moving water below steep, natural grades. Due to this need, two of the initial ditch experiments, Ditches 3 and 4, included efforts to estimate the time needed for diverting water into canals. In both cases, the field crew constructed diversion dams by piling rocks and/or branches in a stream channel in order to raise the water level directly behind it. We then dug the diversion ditch out from the side of the area behind the dam. The dam consisted of pine boughs and sticks at Ditch 3 and rocks at Ditch 4. Each dam allowed about a 5 cm rise in water level and took ten to fifteen minutes to complete.

*Maintenance.* Experimental digging exercises also serve to inform estimates of maintenance needs. Both construction and maintenance would involve the same types of labor in terms of clearing soil with sticks and shovels and rebuilding dam structures. The canal diversion experiments include the most aspects of labor related to maintenance. In particular, one additional take-out experiment conducted in the fall of 2013 focused on diverting fast-moving water from directly below a natural drop in elevation with a slope greater than two degrees. The experiment involved building a rock dam across a 2.5 to 3 m wide stream channel on a steep gradient between 15 to 20 degrees where the Fremont let the water fall naturally. It took six workers half an hour to collect rocks and then place them in the channel. About 0.5 m<sup>3</sup> of rocks contributed to a roughly 60 cm tall dam that raised the water level about 30 cm. Three workers then constructed an 11 meter-long diversion canal from the head of the dam. The canal cut through silty-loam soil of a narrow flood terrace and it curved around to empty back into the stream below the dam. It took approximately two and one half hours to complete the diversion canal with digging sticks. The final feature was about 70 cm wide and 24 to 36 cm deep, with much

of the depth owing to the height of built-up side berms. The head of the canal represented the deepest part at 48 cm. Diverted water ran through the canal at 9 to 6 cm deep and at 0.4 m/s on average. The dam and canal features remain in situ so future monitoring can provide details about the effects of fast water flow, siltation, and seasonal temperature changes on the dam and canal bends. While initial dam construction appears negligible, reconstruction and repair tasks may have occurred multiple times a year on such a steep slope as a result of spring runoff and summer thunderstorms.

*Labor Rate.* Two of the sample ditches, Ditches 2 and 3, remain excluded from rate calculations due to circumstances believed to skew results. Ditch 2 occurred on a wooded, rocky ridge and excavators encountered compacted clay 5 cm below surface. The soil became very hard and severely limited further progress with our tools. Ditch 2 represented one of the dry soil experiments, and the soil type would have responded much better in wet conditions. According to Mabry (2008:235), prehistoric canal builders likely started digging at a water source and the water flow softened dirt, as well as established gradient. Later diversion experiments explored this need. Ditch 3, one of the trials simulating creek diversion, was also excluded as tree roots severely obscured the intake and the ditch bed could not be finished.

The digging experiments for Ditches 1, 4, 5, 6, and 7 produced an average labor rate of 0.29 m<sup>3</sup>/hour for a two-person work crew (Table 3). Extrapolating from this rate, one person could excavate 0.145 m<sup>3</sup>/hour with a digging stick. This rate equates to about 7 hours/m<sup>3</sup> or approximately 1 m<sup>3</sup>/person/day if one considers a work day between six or seven hours. One cubic meter per day falls within the range of excavation rates reported

Table 3. Volume and Labor Rate Calculations

Experiment #	Dirt Volume (m <sup>3</sup> ) ( $[\pi \times r \times h \times l]/2$ )	Time Spent (hr)	Rate (m <sup>3</sup> /hr)	Distance (meters)	Meters/hr
Ditch 1	.59	1.25	.47	3	2.4
Ditch 4	.83	2.67	.31	7.05	2.64
Ditch 5	.33	1.75	.19	3	1.71
Ditch 6	.15	.75	.20	1.1	1.47
Average	.48	1.61	.29	3.54	2.05

elsewhere, especially if including time for rest breaks (Billman 2002; Erasmus 1965; Mabry 2008; Ortloff et al. 1985; Woodbury 1961).

#### *Literature Search*

*Field Labor.* A primary data set for comparative costs and benefits of Fremont dry farming comes from Barlow (1997; 2006), who compiled labor and productivity statistics from dry farming communities in Latin America in order to compare the economics of maize agriculture with foraging. Barlow (1997) models alternative farming strategies based on variable labor inputs that influence energetic benefit. Key variables reported in the analysis include time spent preparing fields, planting, weeding, and harvesting maize. Except for elevated harvest and water allocation costs, time commitment for these tasks would remain much the same between dry and irrigated fields. Several sources supplement Barlow's (1997; 2006) study with additional dry farming data, as well as reported labor information for irrigated maize (Logan and Sanders 1976; Mabry 2005). Barlow (2002) reports that Fremont communities likely spent between 100 and 500 hrs/acre in field investment, while Mabry (2002:183; 2005:137) estimates irrigated field labor at 230 to 382 hrs/acre.

*Processing.* The labor rate of post-harvest maize processing used for this analysis also comes from Barlow's (1997, 2002) published data. Ethnographic observation and experimental work with stone manos and metates established that it takes 43.55 hours to grain, pound, and grind a single bushel of dried maize into meal. Processing time significantly influences energetic return rates for farmers and foragers alike (Barlow 1997; Hawkes and O'Connell 1992). Improvements to processing or handling efficiency will occur if the costs of new processing technology outweigh the benefits of less time spent processing, especially if the technology decreases time spent handling the lowest ranked resources (Hawkes and O'Connell 1992). Any adjustments to processing technology would represent a further investment in the intensification process and could meaningfully increase subsistence return rates. The initial comparison of irrigated and dry maize presented here assumes a constant processing rate to establish the economic relationship of the two techniques prior to improvements in handling technology. The more time spent handling a resource, the more an individual should invest in technology to reduce handling time (Ugan et al. 2003); therefore, investments in processing technology that reduce handling costs would be predictable upon increased reliance on the anticipated yields of irrigated maize.

*Local Environment.* The overall efficiency of the Pleasant Creek canal and success of cultivated maize on Jorgenson Flat depends, in part, on local soil and climate. Soils data received from the Dixie National Forest (Dixie National Forest GIS Database 2013) shows a fine alluvial loam derived from sandstone and shale underlying the upper reaches of the canal. The canal extends northeast through a calcareous gravel alluvium and transitions into sandy alluvium in the lower reaches (Figure 6). Well- to excessively-

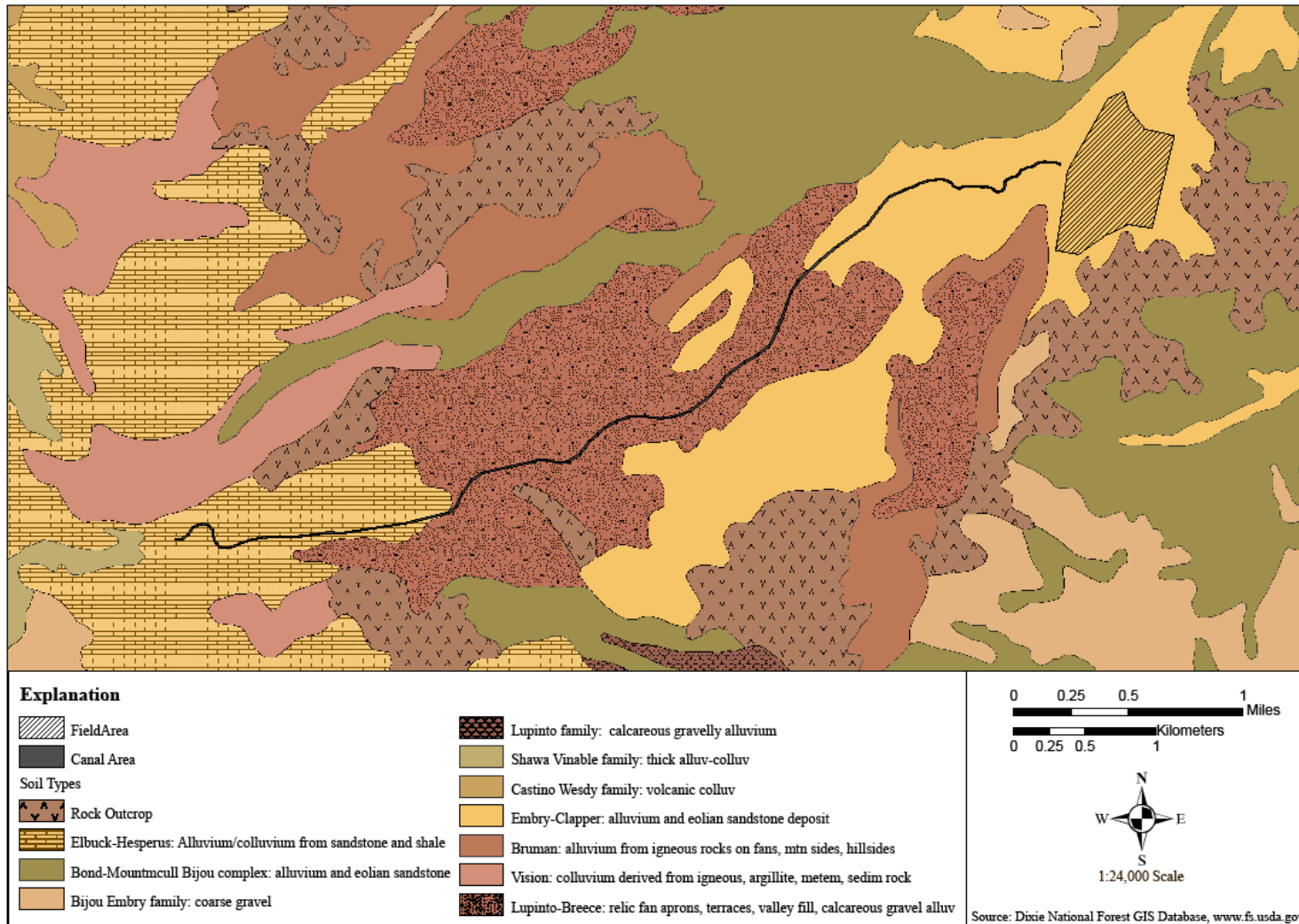


Figure 6. Soil Types Surrounding Pleasant Creek

drained sandy loam soils underlie the Jorgenson Flat field area and much of the canal, indicating potential for high water loss. Elevation also represents a significant consideration for farming on Jorgenson Flat as the area lies just above 7,000 feet. Maize requires a minimum 120-day growing season, and Jorgenson Flat likely experiences a 100- to 140-day frost-free period (Benson et al. 2007; Dixie National Forest GIS Database 2013; Lindsay 1986:238).

Most major excavated Fremont sites occur in areas where farming remains possible in modern times (Lindsay 1986). Talbot (2000b) reports that the Great Basin and Colorado Plateau transition zone receives more than 75 cm annual precipitation in high mountain areas, while lower valleys and canyons receive 25 to 50 cm. Precipitation reports from the mid- to late-twentieth century indicate the Jorgenson Flat area receives between 30 and 40 cm annually (Jensen et al. 1990:4). According to Benson (2011a:6), dry farmed maize requires a minimum of about 15 cm of summer precipitation (i.e., June, July, August, and September) or 30 cm total annual precipitation (Benson 2011b:5). The Pleasant Creek field area may have received just enough annual precipitation to support dry farmed maize. However, annual precipitation records for areas of southern Utah that receive between 25 and 35 cm per year show that summer precipitation may only consist of 10 to 14 cm (Western Regional Climate Center 2011). For example, locations between 6,600 to 7,900 feet elevation from Bryce Canyon National Park, Cedar Point, Widtsoe, and Boulder, Utah received 27 to 35 cm of precipitation annually during a period of record between the 1950s and 2013 (although the record for Widstoe begins in 1912). However only 10.6 to 13.9 cm fell during summer months at these locations (Western Regional Climate Center 2011). This lean summer rainfall could support maize some

years, but years with less precipitation would have seriously reduced crop success, especially considering losses due to natural runoff and evapotranspiration (Anderson and Maass 1987; Dominguez and Holm 2005). Similar areas of Utah, such as the Tavaputs Plateau, experience a one to two year drought about once every five years (Spangler and Spangler 2003). Considering that non-irrigated maize in arid or semi-arid regions may fail to mature fully every third or fourth year (Bradfield 1971:39), the potential for regular or even unexpected drought conditions would provide ample incentive for irrigation on Jorgenson Flat.

#### *Maize Productivity*

Several sources reviewed in the research background provide estimates of dry and irrigated maize productivity. Barlow (1997:190) concludes that dry-farmed maize yields in the Fremont area would range from significantly less than the  $14 \pm 3$  bushels/acre estimated for prehistoric southwestern Colorado to a maximum 12 bushels/acre in more favorable locations. However, elevation represents a potential constraint for maize yields from Jorgenson Flat. Mabry (2005:131-133) reports that early maize crops under *ak chin* (planting on an active alluvial fan), rain fed, or dry techniques in American Southwest environments would yield between 1 and 5 bushels/acre for fields above 5,500 feet elevation. Reports of irrigated maize productivity among subsistence farmers range between 4 and 25 bushels/acre; however not all consider elevation or differences between prehistoric and historic maize varieties (Arbolino 2001; Diehl and Waters 2006; Herhahn and Hill 1998; Logan and Sanders 1976; Mabry 2005). Mabry's (2005:134) estimate, which considers lower yields of prehistoric maize, elevation, and derives from studies in



the northern American Southwest, may represent the best example for irrigated maize yields from Jorgenson Flat. He estimates that irrigated maize above 5,500 feet will yield 250 to 500 kg/ha. Therefore, the yield estimate for high elevation, irrigated maize in a semi-arid region such as the Pleasant Creek location will likely vary between 250 and 500 kg/hectare, or roughly 4 to 8 bushels/acre.

## ANALYSIS

Primary data collected in the field supports calculations for estimating costs and benefits of irrigation at the Pleasant Creek site. Analyzing these factors in terms of a range of outcomes relieves certain problems with modelling prehistoric canal hydraulics and overall productivity. For instance, we do not know the size and design of the entire canal from intake to terminus, information often lacking in studies of ancient irrigation capacity. Details of how natural processes have affected canals over time may also remain deficient due to differential preservation and other constraints on research (i.e. Mabry 2008). Nevertheless, approximations of canal qualities informed by field investigations and cross-cultural analogy help to model a range of hydraulic characteristics directly linked to labor needs, water carrying capacity, and irrigable area. These calculations support assessments of the human carrying capacity and help to develop ideas about the relative scale of agricultural investment at the project site. Modeling the conditions of irrigation at Pleasant Creek allows the site to serve as an analogy, and, ideally, will establish a general relationship between the economics of dry farming and small-scale irrigation that will aid our understanding of irrigation investment across the Fremont region. We can begin looking for more instances of Fremont irrigation based on the environmental parameters and cost-benefit implications established from the Pleasant Creek case.

### *Canal Construction Labor*

Allocation of labor represents investment, and understanding that investment at Pleasant Creek comes through measuring the time spent on labor during initial

construction of the canal, as well as maintenance. The cubic meter per hour labor rate (Table 3) provides an idea of labor required for the Pleasant Creek irrigation feature when multiplied by the estimated amount of soil excavated to construct the canal. I use the dimensions of subsurface channel features exposed in test trenches to estimate the size of the whole system.

The Pleasant Creek canal cross section size likely varied as the channel expanded and contracted in relation to each natural drop and mid-canal diversion. Howard (1993) has previously modeled longitudinal size variability in canal cross-section size elsewhere using a mathematical regression formula. Too few segments of the Pleasant Creek canal remain intact or identified to allow application of such a regression formula to understand total volume. However, the Pleasant Creek estimates will reflect a somewhat larger cross-sectional area closer to the intake because canal cross-sections often become smaller towards the terminus (Billman 2002; Howard 1993:274). The estimate will also take into account that typical transport canals carrying water directly from source to field display some reduction in cross-sectional area, but not as much as canals that feed multiple lateral distributaries (Howard 1993:283). To reflect some size variability, I calculate overall volume here by splitting the canal length into three general size classes between intake and terminus (Table 4).

Table 4. Estimated Constructed Volume

Canal Section	Dimensions	Volume
Top (intake)	120 cm wide x 50 cm deep x 1000 m long	472 m <sup>3</sup>
Middle	110 cm wide x 40 cm deep x 1000 m long	346 m <sup>3</sup>
Bottom (at field)	95 cm wide x 25 cm deep x 1000 m long	187 m <sup>3</sup>
Total Constructed Volume:		1005 m <sup>3</sup>

Field experiments may indicate that diversion points required additional construction labor; however, the added construction time remains relatively small compared to canal building. For example, each of five potential diversion points along the canal could require an additional hour to build, allowing about 30 minutes to build a dam with the remaining time to breach the stream bank and stabilize the dam. The resulting effort of 300 minutes is equivalent to labor expended on digging  $0.7 \text{ m}^3$ . Even if the labor need tripled for initial diversion construction, additional labor would constitute less than  $3 \text{ m}^3$  or three days. The cost of diversion features figure more prominently in maintenance labor than initial construction.

#### *Maintenance Labor*

Ethnographic examples, in conjunction with the experimentally derived labor rate, provide information about maintenance obligations of the irrigation canal. The entire length of the Pleasant Creek canal might be subject to annual maintenance needs. Using the same volume estimates that consider a difference in size between intake and debouchment, the entire canal volume calculation uses three general size classes for each third of the canal length. Woodson (2010:143) reports that annual sediment accumulation representing between one-quarter and three-quarters of canal volume typically characterized maintenance needs in the American Southwest. Regular and repeated repairs to dams and diversion features represent an additional need. I estimate maintenance requirements for the Pleasant Creek canal from a percentage of total canal fill following Woodson (2010) and from experimentally derived labor commitments for building or rebuilding diversion dams.

### *Canal Capacity*

In environments with fluctuating or low annual rainfall, like the northern Colorado Plateau and the American Southwest, water availability characterizes the main constraint on productivity (Dominguez 2002). Irrigation technology represents a way to minimize the limitations of water availability and canal capacity determines irrigable area. We cannot examine the entire length of the Pleasant Creek canal, largely because much of the route remains obscured or destroyed by erosion and historic development. However, the dimensions of subsurface channels exposed in test excavations provide a suitable basis for estimating the hydraulic area for the entire canal. The fact that irrigation channels often decrease in size from intake to terminus also informs this estimate (Billman 2002; Howard 1993). In order to calculate the overall flow of the Pleasant Creek canal, I use averaged statistics for hypothetical canal cross sections from different slope zones along the canal length. Cross sections reflect the three size classes used to calculate soil volume for construction and maintenance (Table 4). The observed channel dimensions from test trenches represents the size category for the lower third of the canal while the upper two thirds reflect slightly larger sizes. Each cross section reflects a unique slope determined from topographic maps of the canal. Equations used to calculate canal capacity include those listed in Table 5.

The current state of research at the project site has not identified the size of field irrigated by the canal. In the absence of this data, we consulted Director of the Utah Water Research Laboratory, Mac McKee, for other ways to demonstrate the total farmed area. McKee suggested an irrigation “rule-of-thumb” maintaining that every farmed

Table 5. Hydraulic Equations

Data	Equation	Variables
Water Velocity (Manning Equation)	$V = (1/N)R^{2/3}S^{1/2}$	R = A/P S = slope N = roughness
Cross-Section Area	$A = \frac{2}{3}Ty$	T = channel top width y = channel depth
Wetted Perimeter	$P = (T/2)[1+x^2 + 1/x \ln(x + 1 + x^2)]$	x = 4y/T
Flow Capacity	$Q = AV$	

hectare requires a flow rate of about one liter per second to deliver an effective level of moisture (Mac McKee, personal communication 2012). Therefore, discharge rate (Q) in cubic meters per second converted to liters and then divided by the one liter/second standard will result in an estimate of total irrigable area. To simulate variation in canal flow resulting from water availability or other practical reasons for operating the canal as below bankfull capacity, I will calculate canal discharge and irrigable area for bankfull, half-full, and quarter-full flow conditions. Additionally, environmental factors such as seepage and evaporation constrain irrigation capacity. Studies of earthen canal seepage and evaporation rates in semi-arid regions indicate that both processes could cause up to 40 percent water loss during conveyance and application of irrigation water (Benson 2011a; Tanji and Kielen 2002). Because of this, I also model canal discharge and irrigable area for different flow conditions affected by 0 to 40 percent water loss.

### *Energetic Benefit*

Kilocalories gained per hour spent in farming labor represents an energetic return rate and measure of harvest efficiency (Kennett et al. 2006). The overall benefit of irrigated maize then derives from the caloric advantage gained as a result of hours spent in canal maintenance, field labor, harvest, and processing. Cross-cultural studies from

analogous environmental conditions provide a range of likely yields for irrigated maize at Pleasant Creek. The estimate used here assumes a yield range of 4 to 8 bushels/acre for maize grown above 5,500 feet. Therefore, the relative efficiency of irrigated maize with respect to dry-farmed maize among the Fremont results from comparing labor costs against the caloric benefit of dry or irrigated maize. The following equations, used by Barlow (1997), calculate the overall energetic benefit of agricultural yield (kcal/hr):

$$\text{Kcal/acre} = X \text{ bushels/acre} \times 25.2 \text{ kg/bushel} \times 3,550 \text{ kcal/kg}$$

$$\text{Kcal/hr spent farming maize} = (\text{kcal/acre}) \div (\text{total hr/acre} [\textit{field labor} + \textit{processing} + \textit{maintenance}])$$

However, the true costs of irrigation technology come not with a single episode of construction and use, but with the continued use of features susceptible to regular erosion and siltation. Labor costs and productivity calculated over a span of multiple years expresses the long-term efficiency of adopting irrigation technology. Averaging total costs over possible years of use shows the span of time affected by initial construction. The following modified equation computes this long-term cost:

$$\text{Kcal/hr} = (\text{kcal/acre}) \div [(\text{canal construction hrs/acre} \div \text{years of operation}) + \text{annual maintenance, field labor, processing hrs/acre}]$$

### *Agricultural Carrying Capacity*

Two parallel calculations help to describe population size associated with irrigation at Pleasant Creek. The first calculation estimates total carrying capacity according to variations in irrigable area. I use an established procedure for estimating

agricultural carrying capacity that involves dividing total caloric yield by some expectation of dietary requirements per person. The FAO (1991) of the United Nations reports that processed maize yields 3,550 kcal/kg and that one person requires an average of 2,000 kcal/day. Total farmed area multiplied by the estimated bushel per acre harvest determines annual caloric yield. According to estimates from stable carbon isotope analysis, maize constituted between 35 and 85 percent of the annual Fremont diet (Coltrain 1993, 1996; Coltrain and Stafford 1999).

The total farmed area, calculated using estimated canal capacity and the resulting area irrigated from this flow, allows estimation of the annual caloric yield of the field area. Farmers may have devoted some field space to crops other than maize, such as squash and beans, or may have chosen not to exploit every available acre. Although investment in irrigation may generally signal a greater reliance on maize, I model the crop yield carrying capacity at Pleasant Creek by simulating populations for which maize represents 35, 50, 65, or 80 percent of the diet under a range of different yield scenarios. The carrying capacity calculation accounts for reductions in yield from storage, seed, or spoilage and includes different field area sizes informed by canal capacity estimates.

The second calculation associated with population size considers how communal work force needs relate to carrying capacity. Population carrying capacity estimates provide an idea of available work force as well as the feasibility of communal construction efforts. The percentage of a population involved in agricultural labor varies among societies, often in relation to the scale of socio-political organization. However, most of the population would be involved in agricultural production in societies that practice subsistence-level agriculture like the prehistoric American Southwest and the



Fremont (Barlow 1997; Doolittle 1991:150). If most of the population supplied labor among the Fremont at Pleasant Creek, then Mabry's (2008:239) estimate suggesting a work force of two-thirds the total population seems plausible when considering gender differences and those too young or old to contribute. Estimated work force sizes needed to complete annual irrigation, field, and processing tasks then suggest total population size; however, this total also remains limited by carrying capacity. Approximations of work force size and carry capacity will be compared to understand this limiting relationship.

## RESULTS

*Canal Construction Costs*

Canal construction costs result from estimates of possible canal size, including only the suspected sections not utilizing natural gradient drops. The total constructed volume for the Pleasant Creek canal could be just over 1,000 m<sup>3</sup>, an estimate based on canal size observed in subsurface test trenches. Sources of variation in the canal volume would derive from the fact that we do not know the exact size of the canal throughout and how the canal size may have varied from intake to terminus. However, the estimate used here approximates the scale of investment at the project site. Table 6 describes the time commitment necessary for constructing a canal of the scale predicted for Pleasant Creek with different labor force sizes working at the experimental labor rate. The results also assume a six-hour workday as suggested by Erasmus (1965) and Doolittle (1984). Communal labor makes a considerable difference in time commitment for canal construction. This scale of construction seems unfeasible for a single individual to attempt and even a group of five would have to labor almost eight months of one year to complete the work. At least ten workers would turn construction into a more reasonable four-month effort, which could allow farmers to construct the feature during months outside of the normal growing season.

Table 6. Time Investment at 0.145 m<sup>3</sup>/hour Construction Rate

Work Force	Hours	Days
1 person	6,930	1,155
5 people	1,386	231
10 people	693	116
20 people	347	58
30 people	231	39

### *Maintenance Costs*

Cross-cultural comparisons suggest that an irrigation canal accumulates between one-quarter and three-quarters of its volume in sediment annually. The entire volume of the Pleasant Creek canal may be as much as 2,400 m<sup>3</sup>, and so the projected annual in-filling of the canal could vary between 600 and 1,800 m<sup>3</sup>. Therefore, annual maintenance costs may include time spent clearing substantial sediment fill. Intake areas and diversion dams would require regular maintenance time, as well. Water diversion experiments show that initial diversion construction could take a group of six workers 30 minutes to complete (or three hrs/diversion for one person), and each diversion would likely need rebuilding at least once a year, although some might need repair more often depending on weather and water flow events. If the Pleasant Creek system included at least five diversion points and all required rebuilding once a year, the modeled time commitment amounts to 15 hours/year for a single person, two and one half hours for a group of five or six, and fewer than two hours a year for larger work groups. I assume here that most maintenance would be accomplished with communal groups, so an individual work effort remains unlikely. If all diversions required maintenance at least five times a year, most of which would occur only during months of use, the time commitment could amount to approximately 15 hours/year for a group of five or six; 25 hours/year with twice the amount of maintenance occasions. When adding this maintenance obligation to the hours estimated for general canal repairs (Table 7), one can see that maintenance represents a significant time commitment every year.

The overall maintenance labor estimated for the Pleasant Creek site takes into account that many sections of the canal cross relatively steep terrain, increasing the

Table 7. Time Investment at 0.145 m<sup>3</sup>/hour Maintenance Rate

1/4 Fill Accumulation		
Work Force	Hours	Days
1 person	4,138	690
10 people	414	69
20 people	207	35
30 people	138	23
3/4 Fill Accumulation		
Work Force	Hours	Days
1 person	12,269	2,045
10 people	1,227	205
20 people	614	103
30 people	409	69

likelihood of scour, erosion, and sediment build-up. However, even given these conditions, an annual maintenance obligation equivalent to removing three-quarters of sediment fill throughout the canal would be unlikely or rare. The modeled maintenance labor for a canal of this size represents an impossible task for one worker, amounting to 23-68 months. The obligation significantly decreases with more workers; however, even a ten-person crew would need to labor about two months to clean out one-quarter fill from the canal length.

Other subsistence tasks, weather, and snow pack limit available days to spend on maintenance. For instance, these tasks would not occur during winter months between December and March/April, eliminating at most five months when maintenance work could not occur. If workers also could not afford to spend time in canal maintenance for one or two months around the time of maize and pine nut harvests, then maintenance work should occur within at least a six month window of time. Under this condition, a work crew of 20 individuals could meet all maintenance volume obligations with one to four months of work. Work groups of 30 to 60 individuals would need to cooperate if the

work were to be finished in less than a month, as commonly done in American Southwest communities (Woodson 2010). Alternatively, ten workers could accomplish a significantly smaller maintenance obligation, such as 800 total person-hours, in two weeks. Factors influencing maintenance needs include not only water flow conditions and soil type, but also differential use of the system each year. Additionally, some irrigation communities may intentionally overbuild canals with the anticipation that natural siltation over time, only diminished by annual maintenance efforts, will reduce canal capacity. In instances of overbuilding, farmers may be less committed to maintenance tasks as long as siltation did not reduce the canal capacity below minimum need. Despite the range of potential maintenance costs associated with Fremont irrigation, the costs remain marginal to the greater annual costs of field labor and maize processing.

#### *Field and Processing Labor*

Cross-cultural studies suggest a range of investments associated with irrigated field labor, which not only includes planting, weeding, and harvesting but also tasks associated with water distribution and water or soil retention. Typical field investment among the Fremont may have ranged between 100 and 500 hrs/acre, but irrigation labor likely fell somewhere toward the higher end of this range. Based on data reported by Mabry (2002) and Logan and Sanders (1976), Fremont irrigated field labor could vary between 230 and 500 hrs/acre. Maize handling costs vary with annual yield and the estimated productivity for the Pleasant Creek field ranges between 4 and 8 bushels/acre. Using the 43.55 hr/bushel processing rate, the expected yield would require between 175 and 350 hours of labor per farmed acre. Together, irrigated field and processing labor for

the project area would require between 400 and 850 hours per acre. This range serves as a basis for modeling total irrigation labor according to a least and most costly scenario.

### *Canal Capacity*

Given the recorded and estimated characteristics of the Pleasant Creek canal, the conveyance system could have supplied water to a relatively large field area. At full capacity, the average canal discharge would be 0.25 m<sup>3</sup> per second, or 252 liters/sec (Table 8). However, canals likely ran at half-full or less (Howard 1993:289; Mabry 2002:193). Average half-full discharge results in 0.13 m<sup>3</sup>/s while 25 percent of total canal capacity equals about 0.06 m<sup>3</sup>/s. Velocity estimates throughout the canal length range from 0.74 m/s near debouchment to 1.6 m/s across elevation drops near the take-out. The potential for relatively high velocity throughout the canal shows the likelihood for scouring and higher maintenance costs (Israelsen and Hansen 1962:84). Running the canal at low capacity may have alleviated some potential for erosive damage.

According to the one liter-per-second-per-hectare rule, the maximum discharge of 252 liters/sec could irrigate up to 622 acres (Table 9). However, this scenario remains unlikely and the total available field area at Pleasant Creek includes only about 135 acres of Jorgenson Flat. Even assuming a 40 percent loss for quarter-full flow, the canal could irrigate at least 90 acres while producing just over 2 acre-feet per day. The 90-acre field size represents a conservative maximum field area for Pleasant Creek farmers.

*Energetic Return Rates.* Assuming a 4 to 8 bushels/acre yield, Pleasant Creek farmers could expect to produce 357,800 to 715,700 kilocalories per acre annually.

Table 8. Average Flow Rate and Discharge

Estimated Canal Sections	Cross-Sectional Area*	Wetted Perimeter*	Velocity*	Discharge Q=AV (m <sup>3</sup> /s)		
	A=(2/3)Ty	P=(T/2)[1+x <sup>2</sup> + 1/x ln (x+1+x <sup>2</sup> )]	V=(1/N)R <sup>(2/3)</sup> S <sup>(1/2)</sup> †	100%	50%	25%
Section 1	.29	2.79	1.26	.37	.19	.09
Section 2	.29	2.79	1.60	.47	.23	.12
Section 3	.29	2.79	1.02	.30	.15	.08
Section 4	.20	2.34	1.42	.28	.14	.07
Section 5	.20	2.34	.85	.17	.09	.04
Section 6	.15	2.04	.95	.14	.07	.04
Section 7	.15	2.04	.74	.11	.06	.03
Section 8	.15	2.04	1.14	.17	.09	.04
<i>Average</i>	.22	2.40	1.12	.25	.13	.06

\* Values reported in meters for area and wetted perimeter and meters/second for velocity

† This equation assumes a channel roughness coefficient, N, value of 0.025 (Farrington 1980:291)

Table 9. Irrigable Acreage after Conveyance and Run-off Losses

Percentage of Water Loss	Average Canal Discharge (liters/sec)			Total Irrigable Acres		
	100% flow	50% flow	25% flow	100% flow	50% flow	25% flow
0%	252	126	64	622	311	157
5%	239	120	60	591	297	149
20%	201	101	51	497	250	126
30%	176	88	45	435	217	110
40%	151	76	38	373	188	94

Kilocalories gained per hour spent in farming labor represent the caloric return rate and measure of harvest efficiency (Kennett et al. 2006). Table 11 shows energetic return rates for irrigated maize from Jorgenson Flat using data summarized in Table 10. The low and high scenarios reflect energetic returns under cost conditions with low or high field and maintenance labor. Additionally, field size significantly conditions overall return rate because of the unique construction and maintenance needs for the Pleasant Creek canal. Logically, a small field plot limits the potential benefit of irrigated maize and emphasizes the expense of constructing large irrigation facilities. Overall, the modeled investment indicates that annual irrigation labor per acre works out to a smaller commitment than other general farming tasks if cultivating at least 25 acres.

Initial construction labor does not directly affect the annual cycle of agricultural labor. However, if divided across years of canal use, initial construction times offer an estimate of how canal use-life effects the overall cost of irrigation. Projected use-life costs over a period of 10 years show that year-to-year labor differences remain relatively small. The effect of initial construction diminishes with greater years of operation. The effect of initial construction diminishes with great years of operation. The greatest differences in return rate manifest between one and four years of operation, and initial



Table 10. Summary of Economic Variables for Irrigation

<b>Costs</b>	
<b>Construction</b>	6,930 total person hours
<i>Per work force of:</i>	
5	1,386 hours
10	613 hours
20	347 hours
30	231 hours
<i>Per farmed area of:</i>	
90 ac	77 hrs/ac
45 ac	154 hrs/ac
25 ac	277 hrs/ac
<b>Maintenance</b>	4,140 – 12,269 total person hours
<i>Per work force of:</i>	
5	830 – 2,455 hrs
10	414 – 1,227 hrs
20	207 – 614 hrs
30	138 – 409 hrs
<i>Per farmed area of:</i>	
90 ac	46 – 136 hrs/ac
45 ac	92 – 273 hrs/ac
25 ac	166 – 491 hrs/ac
<b>Field Work</b>	230 – 500 hrs/ac
<b>Processing</b>	175 – 350 hrs/ac
<b>Benefits</b>	
Irrigable Area	≤ 90 acres
Yield	
<i>Bu/acre</i>	4 – 8
<i>Kcal/acre</i>	357,800 – 715,700

Table 11. Energetic Return Rates for Irrigated Maize on Jorgenson Flat (kcal/hr)\*

Acres	<i>Low Cost Scenario</i>									
	<u>Years</u>									
	1	2	3	4	5	6	7	8	9	10
90	678 – 1,018	731 – 1,077	751 – 1,098	761 – 1,109	767 – 1,116	771 – 1,120	774 – 1,124	777 – 1,126	779 – 1,128	780 – 1,129
45	550 – 866	623 – 956	653 – 989	668 – 1,007	678 – 1,018	685 – 1,026	689 – 1,031	693 – 1,035	696 – 1,039	698 – 1,041
25	422 – 700	504 – 809	539 – 854	559 – 878	571 – 893	580 – 903	586 – 911	591 – 917	595 – 921	598 – 925
15	313 – 543	392 – 658	429 – 709	449 – 737	463 – 755	472 – 767	479 – 776	484 – 783	489 – 789	492 – 793
10	236 – 424	307 – 534	340 – 584	360 – 613	373 – 631	382 – 644	389 – 654	395 – 662	399 – 668	402 – 672
5	137 – 256	186 – 340	211 – 382	226 – 407	237 – 424	244 – 436	250 – 445	254 – 452	258 – 458	260 – 462
	<i>High Cost Scenario</i>									
90	403 – 673	421 – 699	428 – 707	431 – 712	433 – 715	434 – 717	435 – 718	436 – 719	437 – 720	437 – 720
45	325 – 560	349 – 596	358 – 609	363 – 616	366 – 620	367 – 623	369 – 625	370 – 627	371 – 628	371 – 629
25	248 – 442	274 – 484	284 – 499	290 – 507	293 – 513	295 – 516	297 – 518	298 – 520	299 – 522	300 – 523
15	183 – 336	207 – 376	217 – 392	222 – 401	225 – 406	228 – 410	229 – 412	230 – 414	231 – 416	232 – 417
10	138 – 258	159 – 295	168 – 310	172 – 318	175 – 323	177 – 326	179 – 328	180 – 330	181 – 332	181 – 333
5	79 – 153	94 – 179	100 – 190	103 – 196	105 – 200	106 – 202	108 – 204	108 – 206	109 – 207	109 – 208

\* Return rates calculated with  $Kcal/hr = (kcal/acre) \div [(canal\ construction\ hrs/ac \div years\ of\ operation) + annual\ labor\ hrs/ac]$ .  
The reported range represents low and high maize yields in a given year.

costs begin to have a very negligible effect after six years. Therefore, the analysis indicates that a four to six year use-life might best justify irrigation investment at Pleasant Creek, if only by a small margin. If not considering the long-term effects of construction labor, the low-cost scenario for a 25- to 90-acre field returns 627 to 1,587 kcal/hr and the high-cost scenario returns 307 to 882 kcal/hr. Fields less than 15 acres return 1,000 kcal/hr or less for both scenarios. Energetic returns not reflecting construction labor may represent irrigation efficiency for any scenario in which a group of people returned to an irrigation feature they had not used for a period, or even a new group of people migrating into the region and adopting the basic, relatively intact feature to their own use.

The potential energetic return of small-scale irrigation at Pleasant Creek could span the range of efficiencies reported by Barlow (2006:98) for farming investments from a “slash and burn” strategy to intensive agriculture. A dry-farming yield of 1 to 5 bushels/acre represents the comparative productivity used here to compare to irrigated maize yield estimates for the project site. Dry farming does not include the extra labor of annual canal maintenance and so the level of labor for dry farming at the Pleasant Creek location could include between 100 and 500 hrs/acre in field labor and 44 to 220 hrs/acre for processing the expected yield. Mabry (2005) reports a typical yield of 1 to 5 bushels/acre from high elevation fields, resulting from 170 to 180 hrs/acre of labor investment. At 1 to 5 bushels/acre, a yield constrained by low precipitation and high elevation, the Pleasant Creek field could produce 89,400 to 447,300 kilocalories per acre annually. Assuming these costs and benefits, dry farming would return about 400 to 1,100 kcal/hr. While the overall annual yield would vary with field size, the energetic

return rate varies only with the bushel per acre yield. The modeled dry-farming return rate falls within the expected return rate of typical subsistence agriculture as reported by Barlow (2002:81), from 100 to 1,100 kcal/hr (Figure 7).

The potential yield for irrigated fields could represent as much as a 50 percent increase from dry farming yields at similar elevations. If the total labor for dry farming ranges between 144 and 720 hrs/acre and irrigation labor costs between 450 and 1,400 hrs/acre, irrigation investment could represent a 50 to 70 percent increase in labor. As modeled here, Pleasant Creek irrigation farming generally returns lower or equivalent energetic rates compared to dry farming for this area (Table 11). For instance, only high yield estimates for 90-acre fields under the low-cost scenario return energetic rates just over 1,100 kcal/hr. Equivalent return rates occur under the low-cost scenario for high and low yields from fields of 15 acres and greater or only fields 45 acres and greater under

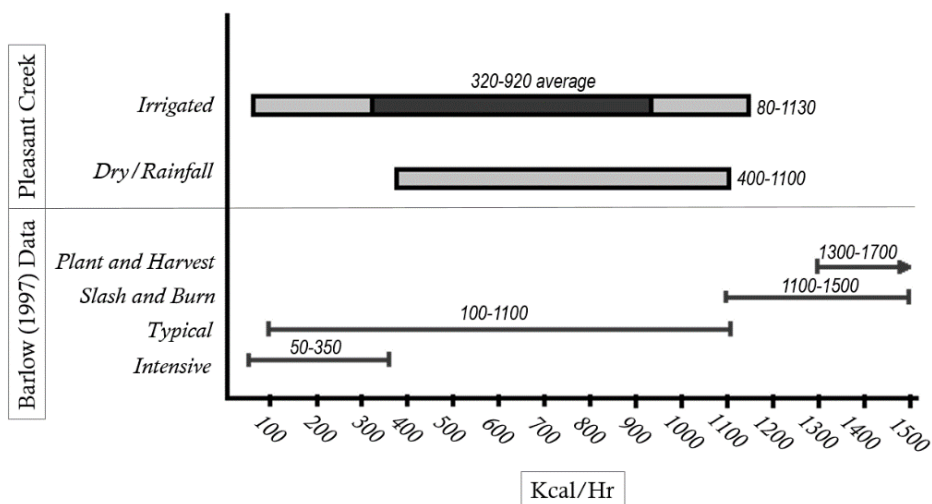


Figure 7. Comparison of Irrigated and Dry-farmed Maize

the high cost scenario. Only high yields for five- to 10-acre plots under the low-cost scenario compete with dry farming, just as only high yields for 15- to 45-acre plots under the high-cost scenario are competitive. Energetic return rates become too low to compete with dry farming strategies of similar yield within the five to 10 acre range at low cost or anything below 15 acres at high cost.

*Agricultural Carrying Capacity.* Annual maize yield estimates for Jorgenson Flat indicate that irrigation could help support a community of 12 to 193 individuals (Table 12). According to the daily caloric requirements of one person, 70 to 160 kg of maize constitute between 35 and 80 percent of one person's annual diet. A combination of small field area, low average yield per unit area, and high caloric demand intuitively suggests a low carrying capacity. The lowest projected populations include those for communities cultivating a smaller field area and relying on maize for 65 to 80 percent of the annual diet. The opposite scenario predicting high yield and lower demand could potentially support almost two hundred people. If a 90-acre plot within the Jorgenson Flat project area averaged at least 6 bushels/acre, maize could provide 65 percent of the diet for roughly 80 individuals. On the other hand, if farmers chose to cultivate somewhat less land, perhaps 45 acres, then maize could supply 65 percent of the diet for only 40 people.

Assessing necessary work group size for total agricultural labor provides another way to estimate population size associated with Pleasant Creek irrigation investment if we assume that a typical workforce represents at least two-thirds of the entire population. The total number of labor hours estimated from average irrigation, field, and processing investments could amount to 59,500 hours for a 90-acre field, 32,500 hours for a 45-acre field, and 21,000 hours for a 25-acre field. As with total maintenance labor, annual

Table 12. Agricultural Carrying Capacity

Yield minus 1/4 for seed and long-term storage (kg)			
	<i>4 bu/ac</i>	<i>6 bu/ac</i>	<i>8 bu/ac</i>
90 Acres	6750	10125	13500
45 Acres	3375	5063	6750
25 Acres	1875	2813	3750
Population Supported by Yield			
Maize in Annual Diet	90 Acres	45 Acres	25 Acres
35% (70 kg)			
<i>4 bu/ac</i>	96	48	27
<i>6 bu/ac</i>	145	72	40
<i>8 bu/ac</i>	193	96	54
50% (100 kg)			
<i>4 bu/ac</i>	68	34	19
<i>6 bu/ac</i>	101	51	28
<i>8 bu/ac</i>	135	68	38
65% (130 kg)			
<i>4 bu/ac</i>	52	26	14
<i>6 bu/ac</i>	78	39	22
<i>8 bu/ac</i>	104	52	29
80% (160 kg)			
<i>4 bu/ac</i>	42	21	12
<i>6 bu/ac</i>	63	32	18
<i>8 bu/ac</i>	84	42	23

construction labor commitments are also constrained by season, weather, and additional subsistence commitments. Annual labor commitments in terms of hours or workdays vary with field size and work group size, making some group sizes less likely when compared with labor time constraints. The division of labor among subsistence agriculturalists in a scenario like the Pleasant Creek site would require at least a 30-person work group to accomplish the annual labor commitment for a 90-acre field (Figure 8). A 45-acre field would require no less than 15 workers while a 25-acre field could just get by with a minimum of 10 workers. If one assumes that each work group size represents two-thirds of the entire population (following Mabry 2008:239), then minimum population size could range between 45 and 15 individuals for 90- to 25-acre field sizes, respectively. If households typically included about five individuals, these figures predict a minimum of three to nine households. However, the minimum carrying capacity and work force need may not directly reflect total population size. The Pleasant Creek field system could support up to 193 individuals or as many as 130 workers. The Pleasant Creek irrigation system could have supported enough workers and non-workers for most field sizes and dietary ranges as long as yields did not fall below 4 bushels/acre (Table 12).

### *Summary*

The preceding analysis provides data on the agricultural costs and benefits of the Pleasant Creek irrigation system. Canal design and volume suggest levels of construction and maintenance costs calculated with replication experiments. These costs, in addition to estimates for field labor and maize processing tasks, constitute annual labor requirements for irrigated maize farming at the project location. Maintenance and field labor costs

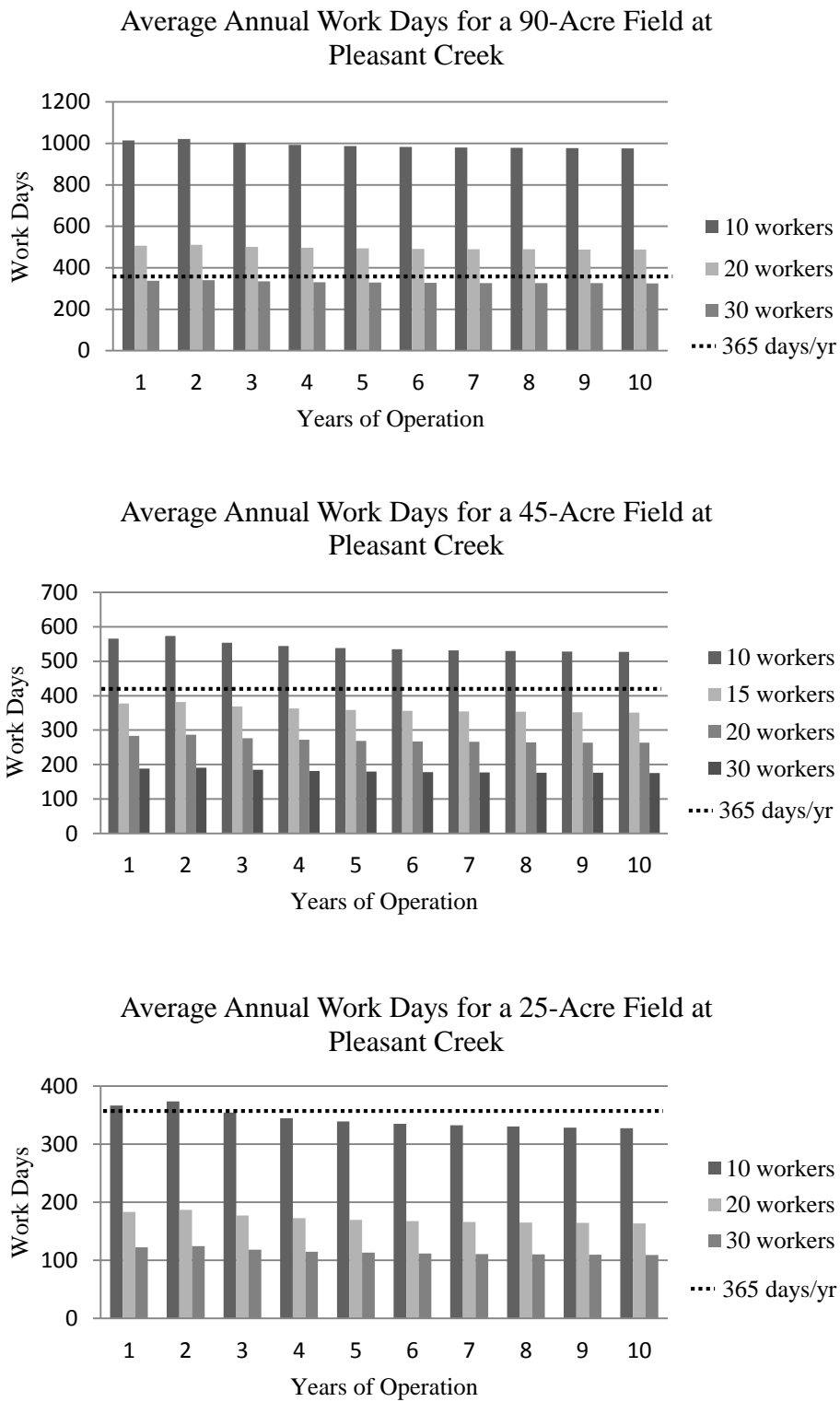


Figure 8. Workdays Required for 90-, 45-, and 25-acre Fields.



could occur as a range of investment, however, and the analysis examines labor requirements for irrigation according to low- and high-cost scenarios to model the efficiency of differential investment. Hydraulic properties of the Pleasant Creek canal indicate a maximum potential irrigable area of 90 acres while cross-cultural studies of irrigated maize in high altitudes suggests each farmed acre could produce between 4 and 8 bushels of maize, or 357,800 to 715,700 kcal/acre annually.

Results show that total cultivated area as well as field and processing labor significantly conditions the energetic return rate of farmed maize. Energetic return rates remain low for field sizes of 15 acres or less and could only compete with dry farming returns (i.e., 400 to 1,000 kcal/hr) involving high yields and low labor costs with these field sizes. Conversely, irrigated maize return rates for field sizes over 25 acres under both high and low labor costs produce equivalent return rates to dry farming under similar environmental conditions. Overall, the modeled return rates for irrigated maize at Pleasant Creek could return between 79 and 1,129 kcal/hr, spanning the ranges between “slash and burn” and intensive agricultural investment strategies as identified by Barlow (1997). An average of costs and benefits predicts a return rate between 320 and 920 kcal/hr. Long-term estimates of efficiency show that initial construction labor ceases to affect energetic return rates after about four to six years while the costs of construction and maintenance influence return rates most with fewer years of canal operation.

The agricultural carrying capacity supported by the Pleasant Creek canal could range between 12 and 193 people, depending on yield, field size, and the proportion of maize in annual diet. The comparison of dry and irrigated maize efficiencies suggests that irrigation would most likely occur with large field sizes and under anticipated yields of at

least 6 or 8 bushels/acre. Additionally, scenarios predicting maize reliance of 65 to 80 percent of the annual diet fit better with expected Fremont diets within the Colorado Plateau (Coltrain 1993). Under these conditions, the population subsisting off an irrigated field on Jorgenson Flat would more likely range between 30 and 100 individuals. This field system could support a community of at least six households or may represent just one plot operated by a larger residential base or dispersed population amounting to about 20 households.

The analysis of factors contributing the effectiveness of small-scale irrigation agriculture suggests several conditions under which the Fremont would irrigate. For instance, Fremont would use irrigation when: (1) marginal returns from foraging and dry farming were low, (2) arable land receiving more than 15 cm of summer precipitation was limited or occupied, and (3) an appropriate workforce of at least more than one five-person family could both be available for labor and supported by the level of agricultural investment. Of course, the scale of irrigation systems like that at Pleasant Creek would require no less than 20 to 30 people to support.

## DISCUSSION

Two research questions posed for the agricultural economics of irrigation at Pleasant Creek aimed to identify the relative efficiency of irrigated maize at the project site and the socio-political implications of the effort. Irrigation represents a level of agricultural intensification known from farming societies around the world but not studied among the Fremont. The Fremont archaeological record provides evidence of agricultural investment and related population growth, characteristics that vary across the culture region and through time. Previous research (Barlow 1997, 2006) established that abundance and availability of high-ranked wild resources influenced the variability in reliance on maize farming among the Fremont, at least during the transition to maize agriculture. However, the study of economic intensification at Pleasant Creek suggests some contexts of selection for intensive investment in maize, much like the Anasazi/Ancestral Puebloan pattern. Further, cross-cultural studies indicate that irrigated agriculture involves a form of intensification often associated with cultural complexity due to population size and managerial density (Boserup 1965; Wittfogel 1957).

### *Irrigated Maize and Efficiency*

The comparison of irrigated maize against dry-farmed or rain fed maize primarily indicates that an irrigation strategy at Pleasant Creek produced resource stability at equivalent or lesser efficiency rates. However, the parameters of productivity for this area prove significantly limiting for both strategies. With an estimated yield of 1 to 5 bushels/acre for dry farming due to elevation, frost-free season, and precipitation, productivity remains relatively low if better-watered, lower elevation areas could produce

12 or more bushels/acre a year (Barlow 1997:190). Therefore, irrigation, a strategy that returns similar benefits but requires up to 60 percent more labor, occurs where surrounding areas could only support low returns for dry farming. Importantly, the energetic return rate of irrigated maize at the project area falls within the same range of dry farming, but also some foraged wild seeds (Barlow 1997; Simms 1985). Irrigation also optimizes growth of wild plant species farmers use, thereby increasing the overall benefit of investing in water control features (Lawton et al. 1976; Stoffle and Zedeño 2001; Winter 1976b).

The economic implication of a decision to invest in irrigation here suggests that opportunities for less expensive farming strategies were limited, or that groups pursued both strategies simultaneously wherever possible. Broad investment in a variety of subsistence strategies characterizes Fremont prehistory. Additionally, archaeologists have found that farming in American Southwest cultures frequently maximized productivity through extensive land use, especially in agriculturally marginal areas (Mabry 2005; Winter 1976b). In either instance, limited land or extensive exploitation may indicate significant population pressure. In a sparsely populated region, groups will relocate once the surrounding environment begins to produce diminished return rates for wild or cultivated foods (Huckell et al. 2002; Van West and Lipe 1992).

Intensification would occur among the Fremont when a population can no longer move to a more suitable area but the needs of a stable or growing population remain constant (Barlow 2006; Boserup 1965). Additionally, while it may seem more likely that communities would invest in irrigation during a drought, irrigation may occur more frequently during periods of environmental abundance when populations and farming

expand across the landscape, exploiting a variety of agricultural strategies (i.e. Lightfoot 1980). Studies of Fremont occupations indicate that sites reflect a pattern of aggregation and disaggregation through time (Talbot and Wilde 1989). According to Massimino and Metcalfe (1999:13), the Fremont complex peaks in terms of population and aggregation between A.D. 700 and A.D. 1000 across the Colorado Plateau, although high incidences of site frequency continue to occur across the Great Basin and the Fremont culture area in general through A.D. 1200 (Massimino and Metcalfe 1999; Talbot and Wilde 1989).

Talbot and Wilde (1989) use radiocarbon dates to suggest distinct episodes of settlement intensity, aggregation, expansion, and disaggregation within this timeframe. For instance, settlement intensity increases with eastward expansion between A.D. 880 and 1040, and settlement reaches the largest geographic extent through westward expansion between A.D. 1040 and 1190. According to the analysis of Massimino and Metcalfe (1999), this second period correlates with continued high site frequency, as well as a possible demographic shift from the northern Colorado Plateau to the Great Basin. Settlement intensity and aggregation then appear to fluctuate and gradually decline between A.D. 1190 and 1350, after which time evidence of Fremont settlement dissipates. Investment in irrigation could represent one of several strategies to exploit a circumscribed territory during periods of Fremont aggregation and expansion.

Pleasant Creek irrigation investment most likely occurred within the peak time-period of Fremont cultural development. Investment would also depend on climatic variation within the wetter warming trend of the Medieval Warm Period that began by A.D. 300 and peaked between A.D. 1000 and 1100s (Simms 2008:88). As in the American Southwest, cycles of settlement and abandonment often follow cycles of

drought and abundance. Current data on paleoclimate in the Pleasant Creek area remains limited; however, even though climate can fluctuate dramatically across regions, recently analyzed dendrochronology records from the Tavaputs Plateau in northeastern Utah indicate that much of Utah corresponds to climate patterns of the northern American Southwest during the Fremont period (Knight et al. 2010). Data from the Mesa Verde region in southwestern Colorado depict agriculturally favorable periods with high water tables between A.D. 1100 and 1130 and A.D. 1180 and 1250 while less-favorable periods occur between A.D. 1130 and 1180 and A.D. 1270 to 1300 (Van West and Dean 2000). Talbot and Wilde (1989) propose that the period between A.D. 1040 and 1190 involved significant Fremont expansion and settlement, corresponding with the early favorable period identified at Mesa Verde, as well as part of a wetter period throughout the A.D. 1000s identified from tree rings on the Tavaputs Plateau (Knight et al. 2010). It appears that some instances of Fremont settlement intensity correspond with generally favorable climate regimes throughout the oscillatory Medieval Warm Period. However, the general trend of increasing settlement intensity between A.D. 700 and 1200 corresponds with a period characterized by a decrease in the scale and magnitude of climate extremes between A.D. 800 and 1200 (Knight et al. 2010).

If communities employ an increasing variety of intensive agricultural strategies with growing settlement intensity and aggregation, then the Pleasant Creek system may have originated between A.D. 1000 and the 1100s. While a warmer and wetter climate characterized this period in general, the time also experienced frequent and sometimes abrupt climate changes that may have lasted one to five years (Simms 2008:90; Van West and Dean 2000). Irrigation would represent an intensive agricultural strategy that allowed

farmers to exploit diverse landscapes while also providing farmers with a way to cope with abrupt changes in temperature and precipitation in an agriculturally marginal location.

### *Socio-political Implications*

Scholars have rarely tried to describe the Fremont as something other than egalitarian farmers. Nevertheless, an increasing number of studies suggest the presence of real complexity within Fremont society (i.e. Coltrain and Leavitt 2002; Janetski et al. 2000; Simms 2008, 2010). The second research question addressed here considers implications of Fremont irrigation at the Pleasant Creek site for our understanding of social organization. Irrigation, itself, does not necessitate the development of complex social relationships or hierarchal organization. However, the communal nature of irrigation labor and productivity implies the existence of defined relationships to manage labor, resource ownership, and harvest distribution that may exist in a society engaged in intensive resource exploitation. The role of intensification strategies like irrigation in forming the Fremont social landscape has not been subject to analysis. I use the relative investment and carrying capacity of irrigated maize at the Pleasant Creek site to explore whether the investment reflected an egalitarian organization versus a society structured by corporate groups or a dynamic sequential hierarchy. Factors involved in this analysis include the complexity of irrigation infrastructure, overall population size associated with the system, and the potential for centralized settlement patterns of the surrounding communities (Table 1).

*Infrastructural Complexity.* Investigation of the Pleasant Creek site through field survey and test excavation has revealed a relatively simple irrigation infrastructure. The system consists of a single transport canal taken from the head of Pleasant Creek to feed Jorgenson Flat. No evidence exists of lateral distribution canals that may feed alternate field locations. In fact, general topography limits the opportunity for such canals and multiple field locations remain unlikely. The lack of multiple canals and fields rules out socio-political complexity, or managerial complexity as identified by Wittfogel (1957), tied to the distribution of water among different levels of communal and private water consumers. Therefore, the overall size of the single canal and need for multiple (up to five) diversion structures represent the measure of infrastructural complexity for this irrigation system, although neither element may involve significant managerial complexity.

Calculations of work force needs for construction and maintenance do indicate that groups of 20 or more workers best met the necessary labor obligations for the system in a given year. Following Johnson's (1983) criteria for socio-political stress among small groups, any group larger than six basal units would spur the development of structured authority because egalitarian, consensus-based decision-making decays with larger groups of people. While socio-political organization varies within small group sizes (Feinman 1995), Johnson's (1983) method of interpreting group size does not necessarily imply strong hierarchical development. It does at least suggest the beginnings of social differentiation based on authority or influence. Additional estimates of general population size further support a socio-political system with the trappings of complexity.



*Population Size.* Estimated population size and labor requirements of Pleasant Creek irrigation support a conclusion that Fremont farmers inhabited a system characterized by resource ownership and status distinctions in addition to communal authority and existent but relaxed hierarchies, perhaps as suggested by Barker (1994) or Simms (2008). Labor and work force requirements suggest a population between at least six and 20 households involved in irrigation tasks (30 to 100 people). Studies of population dynamics indicate that this group size likely involved some form of social status, authority, and hierarchy to manage (Barker 1994; Johnson 1983; Woodburn 1982). Additionally, the estimated population falls just within the range of societies where political authority rises above informal, ephemeral leadership to support one level of authority in the form of a village headman or corporate council (Billman 2002; Feinman and Neitzel 1984).

Cross-cultural studies from various irrigating societies, the American Southwest in particular, offer analogies for complexity among the Fremont (Billman 2002; Mabry 2005, 2008; Vivian 1989). These identify several ways in which irrigation relates to social structure. Irrigation can contribute to social stratification by creating patches of more productive land subject to differential access and inequitable ownership (Flannery 1969). If irrigation efforts do not create complexity, they may still become possible through an existing level of complexity that governs means of resource distribution, conflict resolution, or religious observation (Hunt and Hunt 1976; Mabry 2008). Complexity occurs in different ways and may manifest as centralized, hierarchical organization or heterarchical, horizontal social structure (Hegmon 2005). Indications of

Fremont complexity can come not only from investment in infrastructure, but also from settlement patterns.

*Settlement Characteristics.* One indication of complexity associated with agricultural intensification comes from aggregation and settlement organization. Centralized organization marked by settlement hierarchy often reflects a hierarchical social structure and can serve as an indicator of socio-political complexity (Billman 2002). Fremont researchers have identified a loose settlement hierarchy elsewhere, such as the levels of household, household cluster, supra-household cluster, and dispersed communities discussed in association with the Five Finger Ridge village site (Talbot 2000b). Settlement organization has implications for the availability of labor involved with agricultural intensification. Estimates of labor for the Pleasant Creek site predict the overall population size associated with irrigation efforts; however, the distribution of at least 30 to 100 individuals remains unknown. Aspects of population distribution remain governed by environment, kinship relations, and respective distances to important resources (Simms 2008:223; Talbot 2000b:213).

Many researchers argue that transportation costs influence access to labor and settlement aggregation (Adler et al. 1996; Afolabi Ojo 1973; Blaikie 1971; Found 2010; Leonard and Reed 1993; Stone 1991). Von Thünen (as cited in Blaikie 1971; Found 2010; Stone 1991) and Chisholm (1979) were among the first researchers to address the economic impact of distance between agricultural fields and settlements in small economies. Travel between these loci denotes a labor cost that increasingly detracts from agricultural returns with greater distance (Found 2010:165; Lightfoot 1979; Stone 1991:343). This cost constrains labor availability and leads researchers to conclude that

aggregation should occur in areas where decreased productivity, water shortages, or changes in land availability require labor intensification (Boserup 1965; Cordell and Plog 1979; Leonard 1989; Leonard and Reed 1993).

We cannot make a strong association with centralized settlement at the Pleasant Creek site at this time; nevertheless, site distribution clearly suggests a trend toward clustering and these clusters may be associated with the irrigation feature. Differential distance between the field and site clusters may help to determine the communities associated with the irrigated field. Researchers have defined likely community interaction zones or agricultural catchments elsewhere based on the costs of foot travel and harvest transport (Kohler et al. 1986; Lightfoot 1979; Varien et al. 2000). However, each relied on cross-cultural studies for comparison. Ethnographic evidence from small farming communities reliant on foot travel in the American Southwest, Latin America, India, and Nigeria suggest likely distances between farmers and fields. For example, Bradfield (1971) describes 6.5 km as the usual distance between Hopi fields and dwellings. Hard and Merrill (1992:606) indicate that the Tarahumara of northern Mexico may travel between 2.5 and 8.5 km to fields while Peruvian farmers would rarely plant fields outside a 4 to 5 km territory (Hastorf 1993:122). Blaikie (1971:3) observes that the maximum distance between a village core and fields in northern India ranged between 3 and 5.5 km while irrigated fields frequently occurred less than 1 km from a habitation site. Chisholm (1979) concludes that agricultural activity in Nigeria concentrated within a 1 to 2 km radius of settlements, and activity declines beyond this radius up to at most 5 km due to travel costs.

Current site information for the Pleasant Creek area shows clusters of Fremont sites that occur within 13 km of the field area with scattered sites in between. Some of the sites clearly represent logistic activity areas while others include habitation structures. No one has yet excavated most of these sites or analyzed their spatio-temporal distribution, and the potential for large village sites in the area remains possible. Accepting that even more sites remain undiscovered, our current knowledge of Fremont activity and habitation around Jorgenson Flat seems enough to support the necessary work force and population associated with an irrigated field there, even if residential density remained dispersed. Additionally, the population associated with an irrigated field may represent the work of a corporate group within a larger population set or the communal labor of a devoted, smaller population. More research on the nature of sites around the Pleasant Creek irrigation feature can help to clarify the possibilities of community organization.

## CONCLUSION

A cost and benefit analysis of Fremont irrigation at Pleasant Creek provides insight into the contexts of selection for agricultural intensification. Relevant costs include time spent constructing and maintaining water control features as well as ethnographically derived estimates for field preparation, planting, weeding, and harvesting maize. The comparison of dry and irrigated cultivation scenarios presented here shows little difference in energetic return rates resulting from a significant 50 to 70 percent increase in labor for water management. However, irrigation fails to compete with dry farming efficiency under conditions of low yield (below 4 bushels/acre) and small field size. Additionally, agricultural return rates for dry and irrigated strategies remain significantly conditioned by maize processing labor (Barlow 1997). Irrigation at Pleasant Creek may correspond to continuing reliance on cultivated maize and intensification but not necessarily a wholesale shift to sedentary life and complicated social relationships that touch every aspect of society. More likely, irrigation efforts fit into a marginally complex society already adapted to dealing with issues of resource ownership, status, and authority that arise from resource intensification.

While dry farming may have been possible at Pleasant Creek in some years, investment in irrigation would have made maize fields significantly more productive, as well as predictable. Compared to dry farming efficiency, irrigation represents a strategy to maximize resource exploitation in a way that provided greater reliability in an agriculturally marginal environment. The marginality may have been exploited as a result of population pressure as well as potentially declining returns from foraging and dry

farming on a local or regional scale (Barlow 2006). Given the fluctuating patterns of Fremont settlement, it remains likely that farmers used the Pleasant Creek system periodically over a long span of time. In this case, each period of abandonment would have left the canal in need of significant maintenance and reconstruction, leading to periodically higher irrigation costs. Therefore, the decision to invest in irrigation would play out repeatedly from year to year. From the various suggestions about why or when irrigation occurs, the Fremont might choose to use irrigation when: (1) marginal returns from foraging and dry farming were low, (2) arable land receiving more than 15 cm of summer precipitation was limited or occupied, and (3) an appropriate workforce of at least more than one five-person family could both be available for labor and supported by the level of agricultural investment. Although the chronology of irrigation here remains undefined, Fremont farmers may have used this canal throughout the Medieval Warm Period, during episodes of settlement intensification and expansion (Massimino and Metcalfe 1999; Talbot and Wilde 1989). The Pleasant Creek case provides an example from which to investigate the cultural processes behind decisions to irrigate, as well as to begin looking for more traces of Fremont irrigators based on the environmental and economic relationships established from the project site. While this case study represents a Fremont story, what we gain in understanding about early irrigation investment has significance for studies of agricultural transitions and intensification worldwide.

## REFERENCES CITED

Adams, Robert M.

1971 Early Civilizations, Subsistence, and Environment. In *Prehistoric Agriculture*, edited by Stuart Struever, pp. 591-614. The Natural History Press, Garden City, New York.

Adler, Michael A., Todd Van Pool, and Robert D. Leonard

1996 Ancestral Pueblo Population Aggregation and Abandonment in the North American Southwest. *Journal of World Prehistory* 10:375-438.

Adovasio, James

1979 Comment by Adovasio. *American Antiquity* 44:723-731.

Afolabi Ojo, G.J.

1973 Journey to Agricultural Work in Yorubaland. *Annals of the Association of American Geographers* 63:85-96.

Aikens, C. Melvin

1967 Plains Relationships of the Fremont Culture: A Hypothesis. *American Antiquity* 32:198-209.

1972 Fremont Culture: Restatement of Some Problems. *American Antiquity* 37:61-66.

Anderson, Raymond L., and Arthur Maass

1987 *A Simulation of Irrigation Systems: The Effects of Water Supply and Operating Rules on Production and Income on Irrigated Farms*. Robert E. Krieger, Malabar, Florida.

Arbolino, Risa Diamond

2001 *Agricultural Strategies and Labor Organization: An Ethnohistoric Approach to the Study of Prehistoric Farming Systems in the Taos Area of Northern New Mexico*. Ph.D. dissertation, Southern Methodist University, Dallas. University Microfilms, Ann Arbor.

Arnold Boomgarden, Shannon

2009 An Application of ArcGIS Viewshed Analysis in Range Creek Canyon, Utah. *Utah Archaeology* 22:15-29.

Barker, James P.

1994 Sequential Hierarchy and Political Evolution along the Western Fremont Frontier. Paper presented at the 24<sup>th</sup> Biennial Great Basin Anthropological Conference, Elko, Nevada.

Barlow, K. Renee

1997 Foragers that Farm: A Behavioral Ecology Approach to the Economics of Corn Farming for the Fremont Case. Ph.D. dissertation, University of Utah, Salt Lake City. University Microfilms, Ann Arbor.

2002 Predicting Maize Agriculture among the Fremont. *American Antiquity* 767:65-88.

2006 A Formal Model for Predicting Agriculture among the Fremont. In *Behavioral Ecology and the Transition to Agriculture*, edited by Douglas J. Kennett and Bruce Winterhalder, pp. 87-102. University of California Press, Berkeley and Los Angeles.

2013 Farming, Foraging and Remote Storage in Range Creek: Shifting Strategies of Maize Cultivation, Residential Mobility and Food Storage in Cliff Granaries among



the Fremont of the Northern Colorado Plateau. Manuscript on file with the author, Utah State University Eastern, Prehistoric Museum, Price.

Barlow, K. Renee, and Kerk L. Phillips

2010 Simple Financial Economic Models of Fremont Maize Storage and an Assessment of External Threat. *MPRA* 38251:1-18. Electronic document, <http://mpra.ub.uni-muenchen.de/38251/>, accessed Dec. 3, 2013.

Benson, Larry V.

2011a Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 1: The Southern Colorado Plateau and Rio Grande Regions. *Journal of Archaeological Method and Theory* 18:1-60.

2011b Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 2: The Chaco Halo, Mesa Verde, Pajarito Plateau/Bandelier, and Zuni Archaeological Regions. *Journal of Archaeological Method and Theory* 18:61-109.

Benson, Larry V., Michael S. Berry, Edward A. Jolie, Jerry D. Spangler, David W. Stahle, and Eugene M. Hattori

2007 Possible Impacts of Early-11<sup>th</sup>-, Middle-12<sup>th</sup>-, and Late-13<sup>th</sup>-Century Droughts on Western Native Americans and the Mississippian Cahokians. *Quaternary Science Reviews* 26:336-350.

Bettinger, Robert

1999 What Happened in the Medithermal. In *Models for the Millennium: Great Basin Anthropology Today*, edited by Charlotte Beck, pp. 62-74. University of Utah Press, Salt Lake City.

Billman, Brian R.

2002 Irrigation and the Origins of the Southern Moche State on the North Coast of Peru. *Latin American Antiquity* 13:371-400.

Binford, Lewis R.

1980 Willow Smoke and Dogs' Tails: Hunter-Gatherer Settlement Systems and Archaeological Site Formation. *American Antiquity* 45:4-20.

Bird, Douglas W., and James F. O'Connell

2006 Behavioral Ecology and Archaeology. *Journal of Archaeological Research* 14:143-188.

Blaikie, P.M.

1971 Spatial Organization of Agriculture in Some North Indian Villages: Part I. *Transactions of the Institute of British Geographers* 52:1-40.

Boserup, Ester

1965 *The Conditions of Agricultural Growth*. Aldine Publishing Company, Chicago.

Bradfield, Maitland

1971 *The Changing Pattern of Hopi Agriculture*. Royal Anthropological Institute of Great Britain and Ireland, London.

Bright, Jason, Andrew Ugan, and Lori Hunsaker

2002 The Effect of Handling Time on Subsistence Technology. *World Archaeology* 34:164-181.

Brouwer, C., and M. Heibloem

1986 *Irrigation Water Management: Irrigation Water Needs*. Training Manual No. 3.

Food and Agriculture Organization of United Nations, Rome. Electronic document,

<http://www.fao.org/docrep/S2022E/s2022e00.htm#Contents>, accessed April 22, 2013.

Busch, C.D., L. Mark Raab, and R.C. Busch

1976 Q = A. V: Prehistoric Water Canals in Southern Arizona. *American Antiquity*

41:531-534.

Castetter, Edward F., and Willis H. Bell

1942 *Pima and Papago Indian Agriculture*. University of New Mexico, Albuquerque.

Chisholm, Michael

1979 *Rural Settlement and Land Use: An Essay in Location*. 3<sup>rd</sup> ed. Hutchinson

University Library, London.

Coltrain, Joan Brenner

1993 Fremont Corn Agriculture: A Pilot Stable Carbon Isotope Study. *Utah*

*Archaeology* 6:49-55.

1996 Stable Carbon and Radioisotope Analyses. In *Steinaker Gap: An Early Fremont*

*Farmstead*, edited by Richard K. Talbot and Lane D. Richens. Museum of Peoples

and Cultures Occasional Papers No. 2. Brigham Young University, Provo, Utah.

Coltrain, Joan Brenner, and Steven W. Leavitt

2002 Climate and Diet in Fremont Prehistory: Economic Variability and

Abandonment of Maize Agriculture in the Great Salt Lake Basin. *American*

*Antiquity* 67:453-485.

Coltrain, Joan Brenner, Joel C. Janetski, and Shawn W. Carlyle

2007 The Stable-and Radio-Isotope Chemistry of Western Basketmaker Burials: Implications for Early Puebloan Diets and Origins. *American Antiquity* 72:301-321.

Coltrain, Joan Brenner, and Thomas W. Stafford

1999 Stable Carbon Isotopes and Great Salt Lake Wetlands Diet: Toward an Understanding of the Great Basin Formative. In *Prehistoric Lifeways in the Great Basin Wetlands: Bioarchaeological Reconstruction and Interpretation*, edited by Brian E. Hemphill and Clark S. Larsen, pp. 55-83. University of Utah Press, Salt Lake City.

Cordell, Linda S., and Fred Plog

1979 Escaping the Confines of Normative Thought: A Reevaluation of Puebloan Prehistory. *American Antiquity* 44:405-429.

Damp, Jonathan E., Stephen A. Hall, and Susan J. Smith

2002 Early Irrigation on the Colorado Plateau near Zuni Pueblo, New Mexico. *American Antiquity* 67:665-676.

Davies, Mathew I.J.

2009 Wittfogel's Dilemma: Heterarchy and Ethnographic Approaches to Irrigation Management in Eastern Africa and Mesopotamia. *World Archaeology* 41:16-35.1

Decker, Kenneth W., and Larry L. Tieszen

1989 Isotopic Reconstruction of Mesa Verde Diet from Basketmaker III to Pueblo III. *Kiva* 55:33-46.

Diehl, Michael W.

2011 Risk and Early Agricultural Period Food Plant Use. In *The Latest Research on the Earliest Farmers*, edited by Sarah A. Herr. Online publication, [www.archaeologysouthwest.org/what-we-do/investigations/earliest-farmers](http://www.archaeologysouthwest.org/what-we-do/investigations/earliest-farmers), accessed February 13, 2014.

Diehl, Michael W. (editor)

2005 *Subsistence and Resource Use Strategies of Early Agricultural Communities in Southern Arizona*. Anthropological Papers No. 34. Center for Desert Archaeology, Tucson.

Diehl, Michael W., and Jennifer A. Waters

2006 Aspects of Optimization and Risk during the Early Agricultural Period in Southeastern Arizona. In *Behavioral Ecology and the Transition to Agriculture*, edited by Douglas J. Kennett and Bruce Winterhalder, pp. 63-86. University of California Press, Berkeley and Los Angeles.

Dixie National Forest GIS Database

2013 Soil Unit Map. Electronic ESRI Shapefile, <http://www.fs.usda.gov/main/dixie/landmanagement/gis>, accessed April 23, 2013.

Dominguez, Steven

2002 Optimal Gardening Strategies: Maximizing the Input and Retention of Water in Prehistoric Gridded Fields in North Central New Mexico. *World Archaeology* 34:131-163.

Dominguez, Steven, and Kenneth Holm

2005 Beyond Water Harvesting: A Soil Hydrology Perspective on Traditional Southwestern Agricultural Technology. *American Antiquity* 70:732-765.

Doolittle, William E.

1984 Agricultural Change as an Incremental Process. *Annals of the Association of American Geographers* 74:124-137.

1990 *Canal Irrigation in Prehistoric Mexico: The Sequence of Technological Change*. University of Texas Press, Austin.

1991 A Finger on the Hohokam Pulse. In *Prehistoric Irrigation in Arizona: Symposium*, edited by Cory D. Breternitz, pp. 139-154. Soil Systems Publications in Archaeology No. 17. Soil Systems, Phoenix.

1995 Indigenous Development of Mesoamerican Irrigation. *Geographical Review* 85:301-323.

Earle, Timothy

1980 Prehistoric Irrigation in the Hawaiian Islands: An Evaluation of Evolutionary Significance. *Archaeology and Physical Anthropology in Oceania* 15:1-28.

Eerkens, Jelmer W.

2009 Privatization of Resources and the Evolution of Prehistoric Leadership Strategies. In *The Evolution of Leadership: Transitions in Decision Making from Small-Scale to Middle-Range Societies*, edited by Kevin J. Vaughn, Jelmer W. Eerkens, and John Kantner, pp. 73-94. SAR Press, Santa Fe.

Erasmus, Charles J.

1965 Monument Building: Some Field Experiments. *Southwestern Journal of Anthropology* 21:277-301.

Erickson, Clark L.

1993 The Social Organization of Prehispanic Raised Field Agriculture in the Lake Titicaca Basin. In *Research in Economic Anthropology: Economic Aspects of Water Management in the Prehispanic New World*, edited by Vernon L. Scarborough and Barry L. Isaac, pp. 369-426. JAI Press Inc., Greenwich.

Farrington, Ian S.

1980 The Archaeology of Irrigation Canals, with Special Reference to Peru. *World Archaeology* 11:287-305.

Feinman, Gary

1995 The Emergence of Inequality: A Focus on Strategies and Processes. In *Foundations of Social Inequality*, edited by T. Douglas Price and Gary Feinman, pp. 255-279. Plenum Press, New York.

Feinman, Gary, and Jill Neitzel

1984 Too Many Types: An Overview of Sedentary Prestate Societies in the Americas. *Advances in Archaeological Method and Theory* 7:39-102.

Fish, Suzanne K., and Paul R. Fish

1994 Prehistoric Desert Farmers of the Southwest. *Annual Review of Anthropology* 23:83-108.

Flannery, Kent V.

1969 Origins and Ecological Effects of Early Domestication in Iran and the Near East. In *The Domestication and Exploitation of Plants and Animals*, edited by Peter J. Ucko and Geoffrey W. Dimbleby, pp. 73-100. Aldine, Chicago.

Flannery, Kent V., Anne V.T. Kirkby, Michael J. Kirkby, and Aubrey W. Williams, Jr.

1971 Farming Systems and Political Growth in Ancient Oaxaca. In *Prehistoric Agriculture*, edited by Stuart Struever, pp. 157-178. The Natural History Press, Garden City.

Food and Agriculture Organization

1991 *Production Yearbook 1990*, Vol. 44. United Nations, Rome.

Ford, Richard I.

1992 *An Ecological Analysis Involving the Population of San Juan Pueblo, New Mexico*. Garland Publishing Inc., New York.

Found, William C.

2010 Towards a General Theory Relating Distance between Farm and Home to Agricultural Production. *Geographical Analysis* 2:165-176.

Geertz, Clifford

1972 The Wet and the Dry: Traditional Irrigation in Bali and Morocco. *Human Ecology* 1:23-39.

Grayson, Donald

2011 *The Great Basin: A Natural Prehistory, Revised and Expanded Edition*. University of California Press, Berkeley.

Gremillion, Kristen J.

1996 Diffusion and Adoption of Crops in Evolutionary Perspective. In *Evolutionary Ecology and Archaeology*, edited by Jack M. Broughton and Michael D. Cannon, pp. 335-348. University of Utah Press, Salt Lake City.

Gunnerson, James H.



2009 *The Fremont Culture: A Study in Culture Dynamics on the Northern Anasazi*

*Frontier*. Reprinted. University of Utah Press, Salt Lake City. Originally published 1969, Peabody Museum, Cambridge, Massachusetts.

Hard, Robert J., and William L. Merrill

1992 Mobile Agriculturalists and the Emergence of Sedentism: Perspectives from Northern Mexico. *American Anthropologist* 94:601-620.

Hard, Robert J., Raymond P. Mauldin, and Gerry R. Raymond

1996 Mano Size, Stable Carbon Isotope Ratios, and Macrobotanical Remains as Multiple Lines of Evidence of Maize Dependence in the American Southwest. *Journal of Archaeological Method and Theory* 3:253-318.

Hastorf, Christine A.

1993 *Agriculture and the Onset of Political Inequality before the Inka*. Cambridge University Press, Cambridge, New York.

Hawkes, Kristen, and James O'Connell

1992 On Optimal Foraging Models and Subsistence Transitions. *Current Anthropology* 33:63-66.

Hayden, Brian

1990 Nimrods, Piscators, Pluckers, and Planters: The Emergence of Food Production. *Journal of Anthropological Archaeology* 9:31-69.

Hegmon, Michelle

2005 Beyond the Mold: Questions of Inequality in Southwest Villages. In *North American Archaeology*, edited by T.R. Pauketat and D.D. Loren, pp. 212-234. Blackwell, Malden, Massachusetts.

Herhahn, Cynthia L., and J. Brett Hill

1998 Modeling Agricultural Production Strategies in the Northern Rio Grande Valley, New Mexico. *Human Ecology* 26:469-487.

Holmlund, James P.

2008 Canal Hydraulics. In *Las Capas: Early Irrigation and Sedentism in a Southwestern Floodplain*, edited by Jonathan Mabry, pp. 189-234. Anthropological Papers No. 34. Center for Desert Archaeology, Tucson.

Howard, Jerry B.

1993 A Paleohydraulic Approach to Examining Agricultural Intensification in Hohokam Irrigation Systems. In *Research in Economic Anthropology: Economic Aspects of Water Management in the Prehispanic New World*, edited by Vernon L. Scarborough and Barry L. Isaac, pp. 263-324. JAI Press Inc., Greenwich.

Huckell, Bruce B., Lisa W. Huckell, and Karl K. Benedict

2002 Maize Agriculture and the Rise of Mixed Farming-Foraging Economies in Southeastern Arizona during the Second Millennium B.C. In *Traditions, Transitions, and Technologies: Themes in Southwestern Archaeology*, edited by Sarah H. Schlanger, pp. 137-159. University Press of Colorado, Boulder.

Hunt, Robert C.

1988 Size and the Structure of Authority in Canal Irrigation Systems. *Journal of Anthropological Research* 44:335-355.

2000 Labor Productivity and Agricultural Development: Boserup Revisited. *Human Ecology* 28:251-277.

Hunt, Robert C., and Eva Hunt

1976 Canal Irrigation and Local Social Organization [and Comments and Reply].

*Current Anthropology* 17:389-411.

Hunt, Robert C., David Guillet, David R. Abbott, James Bayman, Paul Fish, Suzanne Fish, Keith Kintigh, and James A. Neely

2005 Plausible Ethnographic Analogies for the Social Organization of Hohokam Canal Irrigation. *American Antiquity* 70:433-456.

Israelsen, Orson Winso, and Vaugh E. Hansen

1962 *Irrigation Principles and Practices*. 3<sup>rd</sup> ed. John Wiley and Sons, New York and London.

Iqbal, Z., R.T. MacLean, B.D. Taylor, F.J. Hecker, and D.R. Bennett

2002 Seepage Losses from Irrigation Canals in Southern Alberta. *Canadian Biosystems Engineering* 44:1.22-1.27.

Janetski, Joel C., and Deborah E. Newman

2000 Fremont Subsistence. In *Clear Creek Canyon Archaeological Project: Results and Synthesis*, edited by Joel C. Janetski, Richard K. Talbot, Deborah E. Newman, Lane D. Richens, and James D. Wilde, pp. 185-200. Museum of Peoples and Cultures, Occasional Papers No. 7. Brigham Young University, Provo, Utah.

Janetski, Joel C., and Richard K. Talbot

2000 Fremont Social and Community Organization. In *Clear Creek Canyon Archaeological Project: Results and Synthesis*, edited by Joel C. Janetski, Richard K. Talbot, Deborah E. Newman, Lane D. Richens, and James D. Wilde, pp. 247-262. Museum of Peoples and Cultures, Occasional Papers No. 7. Brigham Young University, Provo, Utah.

Janetski, Joel C., Richard K. Talbot, Deborah E. Newman, Lane D. Richens, and James D. Wilde

2000 *Clear Creek Canyon Archaeological Project: Results and Synthesis*. Museum of Peoples and Cultures Occasional Papers No. 7. Brigham Young University, Provo, Utah.

Jensen, D.T., Gail E. Bingham, Gaylen L. Ashcroft, Esmail Malek, Greg D. McCurdy, and William K. McDougal

1990 *Precipitation Pattern Analysis: Uinta Basin-Wasatch Front*. Report to Utah Division of Water Resources, Logan.

Johnson, Gregory A.

1983 Decision-making Organization and Pastoral Nomad Camp Size. *Human Ecology* 11:175-199.

Kane, Allen E.

1986 Prehistory of the Dolores River Valley. In *Dolores Archaeological Program: Final Synthetic Report*, edited by David A. Breternitz, Christine K. Robinson, and G. Timothy Gross, pp. 353-435. U.S. Department of the Interior, Bureau of Reclamation, Engineering and Research Center. Denver, Colorado.

Kelly, Robert L.

1997 Late Holocene Great Basin Prehistory. *Journal of World Prehistory* 11:1-49.

Kennett, Douglas J., Barbara Voorhies, and Dean Martorana

2006 An Ecological Model for the Origins of Maize-Based Food Production on the Pacific Coast of Southern Mexico. In *Behavioral Ecology and the Transition to*

*Agriculture*, edited by Douglas J. Kennett and Bruce Winterhalder, pp. 103-136.

University of California Press, Berkeley and Los Angeles.

Knight, Troy A., David M. Meko, and Christopher H. Baisan

2010 A Bimillennial-length Tree-ring Reconstruction of Precipitation for the Tavaputs

Plateau, Northeastern Utah. *Quaternary Research* 73:107-117.

Kohler, Timothy A., Janet D. Orcutt, Eric Blinman, and Kenneth Lee Petersen

1986 Anasazi Spreadsheets: The Cost of Doing Agricultural Business in Prehistoric

Dolores. In *Dolores Archaeological Program: Final Synthetic Report*, edited by

David A. Breternitz, Christine K. Robinson, and G. Timothy Gross, pp. 525-538.

U.S. Department of the Interior, Bureau of Reclamation, Engineering and Research

Center. Denver, Colorado.

Lawton, Harry W., Philip J. Wilke, Mary DeDecker, and William M. Mason

1976 Agriculture among the Paiute of Owens Valley. *The Journal of California*

*Anthropology* 3:13-50.

Leach, Edmund

1959 Hydraulic Society in Ceylon. *Past and Present* 15:2-26.

Lees, Susan H.

1994 Irrigation and Society. *Journal of Archaeological Research* 2:361-378.

Leonard, Robert

1989 Resource Specialization, Population Growth, and Agricultural Production in the

American Southwest. *American Antiquity* 54:491-503.

Leonard, Robert, and Heidi E. Reed

1993 Population Aggregation in the Prehistoric American Southwest: A Selectionist Model. *American Antiquity* 58:648-661.

Lightfoot, Kent G.

1979 Food Redistribution among Prehistoric Pueblo Groups. *Kiva* 44:319-339.

1980 Mormon Sociopolitical Development in Northern Arizona, 1876-1906: Implications for a Model of Prehistoric Change. *Ethnohistory* 27:197-223.

Lindsay, Ian C., and Byron Loosle

2006 The Johnson Rockshelter (Site 42UN2580): An Analysis of Material Remains and Cultural Contexts of a Fremont Storage Site. *Utah Archaeology* 19:1-20.

Lindsay, La Mar W.

1986 Fremont Fragmentation. In *Anthropology of the Desert West: Essays in Honor of Jessie D. Jennings*, edited by Carol J. Condie and Don D. Fowler, pp. 229-251. University of Utah Press, Salt Lake City.

Logan, Michael H., and William T. Sanders

1976 The Model. In *The Valley of Mexico: Studies in Pre-Hispanic Ecology and Society*, edited by Eric R. Wolf, pp. 31-58. University of New Mexico Press, Albuquerque.

Mabry, Jonathan B.

2002 The Role of Irrigation in the Transition to Agriculture and Sedentism in the Southwest: A Risk Management Model. In *Traditions, Transitions, and Technologies: Themes in Southwestern Archaeology, Proceedings of the 2000 Southwest Symposium*, edited by Sarah H. Schlanger, pp. 178-199. University Press of Colorado, Boulder.

2005 Diversity in Early Southwestern Farming and Optimization Models of Transitions to Agriculture. In *Subsistence and Resource Use Strategies of Early Agricultural Communities in Southern Arizona*, edited by Michael Diehl, pp. 113-152. Anthropological Papers No. 34. Center for Desert Archaeology, Tucson.

Mabry, Jonathan B. (editor)

2008 *Las Capas: Early Irrigation and Sedentism in a Southwestern Floodplain*. Anthropological Papers No. 28. Center for Desert Archaeology, Tucson.

Madsen, David

1979 New Views on the Fremont: The Fremont and the Sevier: Defining Prehistoric Agriculturalists North of the Anasazi. *American Antiquity* 44:711-722.

Madsen, David, and Steven Simms

1998 The Fremont Complex: A Behavioral Perspective. *Journal of World Prehistory* 12:255-336.

Martin, Steve L.

1999 Virgin Anasazi Diet as Demonstrated through the Analysis of Stable Carbon and Nitrogen Isotopes. *Kiva* 64:495-514.

Marwitt, John P.

1970 *Median Village and Fremont Culture Regional Variation*. Anthropological Papers No. 95. University of Utah, Salt Lake City.

Masse, W. Bruce

1981 Prehistoric Irrigation Systems in the Salt River Valley, Arizona. *Science* 214:408-415.

Massimino, Jacquelyn, and Duncan Metcalfe

1999 New Form for the Formative. *Utah Archaeology* 12:1-16.

Matson, R.G.

1999 The Spread of Maize to the Colorado Plateau. *Archaeology Southwest* 13:10-11.

Matson, R.G., and Brian Chisholm

1991 Basketmaker II Subsistence: Carbon Isotopes and Other Dietary Indicators from Cedar Mesa, Utah. *American Antiquity* 56:444-459.

McGuire, Randall H., and Dean J. Saitta

1996 Although They Have Petty Captains, They Obey them Badly: The Dialectics of Prehispanic Western Pueblo Social Organization. *American Antiquity* 61:197-216.

Merrill, William L.

1983 Tarahumara Social Organization, Political Organization, and Religion. In *The Handbook of North American Indians, Volume 10*, edited by William C. Sturtevant, pp. 290-305. Smithsonian Institution, Washington, D.C.

Metcalf, Duncan, and Lisa Larrabee

1985 Fremont Irrigation: Evidence from Gooseberry Valley, Central Utah. *Journal of California and Great Basin Anthropology* 7:244-254.

Mitchell, William P.

1973 The Hydraulic Hypothesis: A Reappraisal. *Current Anthropology* 14:532-534.

1976 Irrigation and Community in the Central Peruvian Highlands. *American Anthropologist* 78:25-44.

Morss, Noel



2009 *The Ancient Culture of the Fremont River in Utah*. Reprinted. University of Utah Press, Salt Lake City. Originally published 1931, Peabody Museum, Harvard University, Cambridge, Massachusetts.

Netting, Robert McC.

1974 Agrarian Ecology. *Annual Review of Anthropology* 3:21-56.

Ortloff, Charles R., Robert A. Feldman, and Michael E. Moseley

1985 Hydraulic Engineering and Historical Aspects of the Pre-Columbian Intravalley Canal Systems of the Moche Valley, Peru. *Journal of Field Archaeology* 12:77-98.

Rautman, Alison E.

1998 Hierarchy and Heterarchy in the American Southwest: A Comment on McGuire and Saitta. *American Antiquity* 63:325-333.

Rice, Prudence M.

2008 On Classic Maya Political Economies. *Journal of Anthropological Archaeology* 28:70-84.

Roth, Barbara J., and Andrea Freeman

2008 The Middle Archaic Period and the Transition to Agriculture in the Sonoran Desert of Southern Arizona. *Kiva* 73:321-353.

Sammons-Lohse, Dorothy

1981 Households and Communities. In *Bull Creek*, edited by Jesse D. Jennings and Dorothy Sammons-Lohse, pp. 111-135. Anthropological Papers No. 105. University of Utah, Salt Lake City.

Sanders, William T., and Deborah L. Nichols

1988 Ecological Theory and Cultural Evolution in the Valley of Oaxaca. *Current Anthropology* 29:33-80.

Scarborough, Vernon L.

1991 Water Management Adaptations in Nonindustrial Complex Societies: An Archaeological Perspective. *Archaeological Method and Theory* 3:101-154.

Scarborough, Vernon L., Fred Valdez Jr., and Nicholas Dunning (editors)

2003 *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East Central Yucatan Peninsula*. University of Arizona Press, Tucson.

Simms, Steven R.

1985 Cost and Nutritional Data on Great Basin Resources. *Journal of California and Great Basin Anthropology* 7:117-126.

1986 New Evidence for Fremont Adaptive Diversity. *Journal of California and Great Basin Anthropology* 8:204-216.

1990 Fremont Transitions. *Utah Archaeology* 3:1-18.

2008 *Ancient Peoples of the Great Basin & Colorado Plateau*. Left Coast Press, Walnut Creek, California.

2010 *Traces of Fremont: Society and Rock Art in Ancient Utah*. University of Utah Press, Salt Lake City.

Simms, Steven R., and Chimalis Kuehn

2012 *The Archaeology of Ancient Fremont Irrigation*. Utah State University.

Submitted to USDA Forest Service, Project No. U-12-UJ-0985f. Copies available from Utah State History.

Simms, Steven R., Chimalis R. Kuehn, and Nancy Kay Harrison

2012 The Archaeology of Ancient Fremont Irrigation. Poster presented at the 33<sup>rd</sup> Biennial Great Basin Anthropological Conference, South Lake Tahoe.

Skogerboe, Gaylord V., and Gary P. Merkley

1996 *Irrigation Maintenance and Operations Learning Process*. Water Resources Publications, LLC. Highlands Ranch, Colorado. Google Book.

Smith, Eric Alden

1983 Anthropological Applications of Optimal Foraging Theory: A Critical Review. *Current Anthropology* 24:625-651.

Spangler, Jerry D.

2013 *Nine Mile Canyon: The Archaeological History of an American Treasure*. University of Utah Press, Salt Lake City.

Spangler, Jerry D., and Donna K. Spangler

2003 *Horned Snakes and Axle Grease: A Roadside Guide to the Archaeology, History, and Rock Art of the Nine Mile Canyon*. Uinta Publishing, Salt Lake City.

Steward, Julian

1955 *Irrigation Civilizations: A Comparative Study*. Pan American Union, Washington, D.C.

Stoffle, Richard W., and Maria Nieves Zedeño

2001 Historical Memory and Ethnographic Perspectives on the Southern Paiute Homeland. *Journal of California and Great Basin Anthropology* 23:229-248.

Stone, Glenn Davis

1991 Agricultural Territories in a Dispersed Settlement System. *Current Anthropology* 32:343-353.

Talbot, Richard K.

2000a Fremont Architecture. In *Clear Creek Canyon Archaeological Project: Results and Synthesis*, edited by Joel C. Janetski, Richard K. Talbot, Deborah E. Newman, Lane D. Richens, and James D. Wilde, pp. 131-184. Museum of Peoples and Cultures, Occasional Papers No. 7. Brigham Young University, Provo, Utah.

2000b Fremont Settlement Patterns and Demography. In *Clear Creek Canyon Archaeological Project: Results and Synthesis*, edited by Joel C. Janetski, Richard K. Talbot, Deborah E. Newman, Lane D. Richens, and James D. Wilde, pp. 201-230. Museum of Peoples and Cultures, Occasional Papers No. 7. Brigham Young University, Provo, Utah.

Talbot, Richard K., and Lane D. Richens

1996 *Steinaker Gap: An Early Fremont Farmstead*. Museum of Peoples and Cultures Occasional Papers No. 2. Brigham Young University, Provo, Utah.

Talbot, Richard K., and James Wilde

1989 Giving Form to the Formative. *Utah Archaeology* 2:3-18.

Tanji, Kenneth K., and Neeltje C. Kielen

2002 *Agricultural Drainage Water Management in Arid and Semi-Arid Areas*. FAO Irrigation and Drainage Paper 61. Food and Agricultural Organization of the United Nations, Rome. Electronic document, <http://www.fao.org/docrep/005/y4263e/y4263e00.htm#Contents>, accessed April 22, 2013.

Ugan, Andrew, Jason Bright, and Alan Rogers

2003 When is Technology Worth the Trouble? *Journal of Archaeological Science* 30:1315-1329.

United States Department of the Interior, Bureau of Reclamation

1968 *Irrigation Operation and Maintenance: Measuring Seepage in Irrigation Canals by the Ponding Method*. Bulletin No. 65. Division of Irrigation Operations. Denver, Colorado.

Upham, Steadman

1994 Nomads of the Desert West: A Shifting Continuum in Prehistory. *Journal of World Prehistory* 8:113-167.

Uphoff, Norman

1992 *Learning from Gal Oya: Possibilities for Participatory Development and Post-Newtonian Social Science*. Cornell University Press, Ithaca, New York.

Van West, Carla R., and Jaffrey S. Dean

2000 Environmental Characteristics of the A.D. 900-1300 Period in the Central Mesa Verde Region. *Kiva* 66:19-44.

Van West, Carla R., and William D. Lipe

1992 Modeling Prehistoric Climate and Agriculture in Southwestern Colorado. In *The Sand Canyon Archaeological Project: A Progress Report*, edited by William D. Lipe, pp. 105-119. Crow Canyon Archaeological Center Occasional Paper No. 2. Cortez, Colorado.

Varien, Mark D., Carla R. Van West, and G. Stuart Patterson

2000 Competition, Cooperation, and Conflict: Agricultural Production and Community Catchments in the Central Mesa Verde Region. *Kiva* 66:45-65.

Vivian, R. Gwinn

1989 Kluckhohn Reappraised: The Chacoan System as an Egalitarian Enterprise. *Journal of Anthropological Research* 45:101-113.

Welch, John R.

1996 The Dry and the Drier: Cooperation and Conflict in Moroccan Irrigation. In *Canals and Communities: Small-Scale Irrigation System*, edited by Jonathan B. Mabry, pp. 69-87. University of Arizona Press, Tucson.

Western Regional Climate Center

2011 *Utah: Monthly Average Precipitation (inches)*. Electronic document, <http://www.wrcc.dri.edu>, accessed October 7, 2013.

Wilde, James D., and Deborah E. Newman

1989 Late Archaic Corn in the Eastern Great Basin. *American Anthropologist* 91:712-720.

Wilde, James D., Deborah E. Newman, and Andrew E. Godfrey

1986 *The Late Archaic/Early Formative Transition in Central Utah: Pre-Fremont Corn from the Elsinore Burial, Site 42SV 2111, Sevier County, Utah*. Museum of Peoples and Cultures Technical Series No. 86-20. Brigham Young University, Provo, Utah.

Wills, W.H.

1988 Early Agriculture and Sedentism in the American Southwest: Evidence and Interpretation. *Journal of World Prehistory* 2:445-488.

Winter, Joseph

1973 The Distribution and Development of Fremont Maize Agriculture: Some Preliminary Interpretations. *American Antiquity* 38:439-452.

1976a The Processes of Farming Diffusion in the Southwest and Great Basin. *American Antiquity* 41:421-429.

Winter, Joseph (editor)

1976b *Hovenweep 1975*. Archaeological Report No. 2. Anthropology Department, San Jose State University, San Jose, California.

Winter, Joseph, and Henry G. Wylie

1974 Paleoecology and Diet at Clydes Cavern. *American Antiquity* 39:303-315.

Winterhalder, Bruce, Flora Lu, and Bram Tucker

1999 Risk-Sensitive Adaptive Tactics: Models and Evidence from Subsistence Studies in Biology and Anthropology. *Journal of Archaeological Research* 7:301-348.

Wittfogel, Karl

1957 *Oriental Despotism: A Comparative Study of Total Power*. Yale University Press, New Haven, Connecticut.

1971 Developmental Aspects of Hydraulic Societies. In *Prehistoric Agriculture*, edited by Stuart Struever, pp. 557-571. The Natural History Press, Garden City.

Woodburn, James

1982 Egalitarian Societies. *Man* 17:431-451.

Woodbury, Richard B.

1961 A Reappraisal of Hohokam Irrigation. *American Anthropologist* 63:550-560.

Woodbury, Richard B., and James A. Neely

1972 Water Control Systems of the Tehuacan Valley. In *The Prehistory of the Tehuacan Valley, Volume 4: Chronology and Irrigation*, edited by Frederick Johnson, pp. 81-161. University of Texas, Austin.

Woodson, Michael Kyle

2007 Building and Cleaning the Snaketown Canal. *Archaeology Southwest* 21:13.

2010 The Social Organization of Hohokam Irrigation in the Middle Gila River Valley, Arizona. Master's thesis, Arizona State University, Tempe. University Microfilms. Ann Arbor.

Woosley, Anne I.

1980 Agricultural Diversity in the Prehistoric Southwest. *Kiva* 45:317-335.

Yoder, David T.

2005 Storage and Mobility among the Fremont: Changing Forms through Time. Unpublished Master's thesis, Department of Anthropology, Brigham Young University, Provo, Utah.